# RECEIVER DESIGN IN A COMMERICAL, MARINE, SINGLE-SIDEBAND TRANSCEIVER

by

Richard Warren Hamon

# UNITED STATES
# NAVAL POSTGRADUATE SCHOOL

# THESIS

RECEIVER DESIGN IN A COMMERCIAL,

MARINE, SINGLE-SIDEBAND TRANSCEIVER

By

Richard Warren Hamon

September 1968

RECEIVER DESIGN IN A COMMERCIAL,

MARINE, SINGLE-SIDEBAND TRANSCEIVER

By

Richard Warren Hamon
Lieutenant, United States Navy
B S., U. S. Naval Academy, 1960

[redacted]

Submitted in partial fulfillment
for the degree of

MASTER OF SCIENCE IN ENGINEERING ELECTRONICS

from the

NAVAL POSTGRADUATE SCHOOL
September 1968

ABSTRACT

Design of the receiver portion of a solid-state, state-of-the-art, single-sideband, 2-17 MHz transceiver is presented. A short comparison of amplitude-modulated and single-sideband systems is offered. The unique requirements of commercial, marine communications are considered and the method of their fulfillment in this transceiver is discussed. Circuitry common to both receiver and transmitter is presented in detail. Receiver testing and specific results are included.

# TABLE OF CONTENTS

| Section | Page |
|---|---|
| Introduction | 7 |
| Objective | 10 |
| Specifications | 11 |
| General | |
| Transmitter | |
| Receiver | |
| Receiver Design Considerations | 13 |
| Radio-Frequency Amplfier | |
| Mixer | |
| Crystal Filter | |
| Intermediate-Frequency Amplifier | |
| Product Detector | |
| Audio Driver and Output Amplifier | |
| AM and AGC Detector | |
| Squelch | |
| Internal Power Distribution | |
| Oscillator Section | |
| Switching | 25 |
| Channel Selection | |
| Signal Flow and Automatic AM | |
| Oscillator Switching | |
| Receiver Testing | 31 |
| Sensitivity | |
| Selectivity | |

Page

Automatic Gain Control

Spurious Responses

Squelch Control

Cross-modulation Distortion

Intermodulation Distortion

Bibliography . . . . . . . . . . . . . . . . . . . . . . 39

Appendix

I Comparison of SSB and AM Systems . . . . . . . . 40

II Receiver Schematic Diagram . . . . . . . . . . 41

Component List . . . . . . . . . . . . . . . . . 49

III Receiver Test Results . . . . . . . . . . . . . 53

## LIST OF ILLUSTRATIONS


| Figure | | Page |
|---|---|---|
| 1 | Receiver Block Diagram | 14 |
| 2 | Audio Driver Functional Diagram | 20 |
| 3 | Internal Power Distribution | 23 |
| 4 | RF Amplifier Input Switching | 27 |
| 5 | Automatic AM Switching | 28 |
| 6 | Oscillator Switching | 30 |
| 7 | BFO Switching | 32 |
| 8 | Test Setups | 33 |
| 9 | Test Setups | 38 |

## INTRODUCTION

The high-frequency (HF) spectrum (2-30 MHz) offers a unique propagation characteristic (sky wave mode) and is consequently in great demand by both commercial and military activities. Sky wave (ionospheric reflection) propagation is a mode of considerable importance in long range communications (6). Since the available HF channels are limited, highly spectrum conservative systems must be utilized. Minimum bandwidth, small guard bands between channels (which implies extremely stable frequency generation) and low values of spurious radiation are essential to effective employment of this extremely useful frequency range. Single-sideband communication systems meet these requirements.

The Federal Communications Commission (FCC) has recognized the growing demand for channels in this range and has ruled that all new shipboard licenses issued after 1 January 1970 and all license renewals after 1 January 1974 will be only for single side-band (SSB) in the 4.0-27.5 MHz frequency band. The same restrictions apply to shore stations for both new and renewal licenses after 1 January 1973 (2). It is very probable that the ruling will be extended to the 2.0-4.0 MHz marine band in the near future.

It is therefore apparent that any new transceiver designed for commercial, offshore communications should be for single side-band (SSB). At present, most marine communication in the HF band is by the amplitude-modulation (AM) mode. Hence, the transceiver should also be compatible for AM (A3H) (3). This will permit its immediate acceptance by this large market and would also allow its continued use in the 2.0-4.0 MHz marine band if the FCC continues to endorse AM in that region. A further requirement for a competitive marine transceiver is that it have a ship-to-shore capability. Many coastal stations require the -16 db pilot carrier (SSB, reduced carrier, A3A) for commercial ship-to-shore communications (3). The FCC requirement for SSB in this portion of the high-frequency spectrum will be a major change for marine users. In general, the price of converting an AM set to SSB is prohibitive and thus a lucrative SSB market appears to be forming in the commercial, offshore communications area.

Single-sideband equipment is more complex than comparable AM equipment. In SSB systems, an AM waveform must first be generated and then only one sideband (vice both sidebands plus carrier in AM) is transmitted (SSB, suppressed carrier, A3J emission). Some means of removing one of the sidebands is required. This selection process is accomplished at low signal levels and then the selected sideband receives the final power boost prior to transmission. Since no carrier is transmitted, very precise ($\pm$ 20 Hz) radio-frequency generation is mandatory. Both of these requirements increase the complexity and therefore the cost of SSB equipment.

Aside from the extremely advantageous feature of narrower bandwidth, SSB has other characteristics which render it superior to AM. Due to the unique character of SSB, a simple comparison with AM is difficult. The concise comparison in Appendix I will serve to illustrate the advantages of SSB. The following assumptions are made:

(a) Equal signal-to-noise (S/N) ratios in the receivers.

(b) Both systems use single-tone, sine-wave modulation (100% for AM).

(c) AM carrier power of one watt.

(d) SSB peak envelope power (PEP) of 0.5 watts. PEP is defined as the RMS power developed at the crest of the modulation envelope.

(e) Coherent (in-phase) detection in the AM receiver.

(f) Receivers have equal noise figures (NF).

(g) The SSB predetection bandwidth (B) is one-half that of AM.

(h) Ideal propagation conditions exist.

Note that the 3 db coherent detection advantage gained by the AM system is negated by a 3 db greater noise level in that system. The rated one-half watt PEP of the SSB system produces the same level of intelligibility of the received signal as the one watt rated (carrier power) AM system.

Peak antenna voltages are of special importance in mobile equipment where the antennas are, in general, electrically short. Corona breakdown at the antenna is often the limiting consideration on equipment power. The peak antenna voltage for SSB equipment is about one-third that of a comparable AM system. Another advantage of significant importance is the insensitivity of SSB to selective fading. Three types of selective fading which produce distortion in AM are: sideband fading, carrier fading and relative phase-shift fading. Fading of one sideband in AM results in a loss of detected signal voltage. Since the receiver noise bandwidth is constant, a degradation of the S/N ratio results. The most serious and unfortunately the most common selective fading problem in AM is carrier fade. In this case the carrier is attenuated more than the sidebands. A carrier voltage at least as great as the sum of the sideband voltages is necessary to properly demodulate the RF envelope. Normally in AM the resultant of the two sideband phasors is either zero, in phase or 180 degrees out of phase with the carrier. If the carrier is shifted in phase, then this phasor relationship does not hold true. The RF waveform and the demodulated signal are therefore distorted (1). Exhalted carrier techniques ease the effects of the last two problems. In contrast, selective fading in a SSB system can only change the amplitude of the received signal. It rarely causes enough distortion to render the signal unintelligible.

The principle advantages of SSB over AM are therefore: (a) Spectrum and power economy (b) Superior performance under adverse propagation conditions.

## OBJECTIVE

The overall objective is to design, build and submit for Federal Communication Commission (FCC) certification a state-of-the-art, solid-state (where feasible), SSB transceiver. The transmitter section will be briefly included for completeness. Certain common circuitry will, however, be fully investigated.

This SSB receiver incorporates modern solid-state devices. Full use is made of integrated circuitry (IC), metal-oxide, semiconductor, field-effect transistors (MOSFETs), crystal filters and printed circuit (PC) boards. This is a commercial, mobile transceiver and hence weight, compactness, production cost and receiver/transmitter compatibility are prime design considerations.

# SPECIFICATIONS

## GENERAL

| | |
|---|---|
| Frequency Range | 2-17 MHz |
| Preset Channels (Crystal controlled) | 12 (7 Simplex and 5 Simplex or Semiduplex) |
| Operating Modes | SSB (A3J)<br>Compatible AM (A3H)<br>Ship-to-shore (A3A) |
| Transmission and Reception | USB on all modes |
| Power Input Requirements (Power Supply-Separate Unit) | 20 watts-Standby<br>500 watts-Peak Transmit |
| Dimensions (Including Antenna Coupler) | 18W X 8H X 10D (inches) |
| Weight (Including Antenna Coupler) | 30 LBS |
| Antenna Coupler | Detachable, matches unbalanced 50 ohms to long wire or whip antenna |

## TRANSMITTER

| | |
|---|---|
| Output Power | SSB: 250 watts PEP (Automatically reduced to 150 watts on 2-4 MHz as required by the FCC)<br>Compatible AM: 60 watts carrier power |
| Output Impedance | 50 ohms, unbalanced |
| Intermodulation Distortion Products (2-tone, 3rd-order) | -40 db, minimum |
| Spurious Output: | |
| Carrier | -40 db, minimum |
| Lower Sideband | -40 db, minimum |
| Second Harmonic | -40 db, minimum |
| Audio Response | 400-2500 Hz |
| Frequency Stability | $\pm$ 20 Hz |

RECEIVER

| | |
|---|---|
| Sensitivity (10 db S+N/N ratio) | SSB: 0.5 uV<br>AM: 3 uV |
| Selectivity | SSB: 2.1 kHz<br>AM: 10 kHz |
| Image Rejection | -50 db |
| Audio Output Power | 2 watts into 4 ohms |
| AGC Characteristics | Fast Attack/Slow Decay |

In order to simplify operator functions, this transceiver has many built-in automatic features. The front panel incorporates the following controls: (1) Press-to-talk button on the microphone (S-1), (2) Mode switch (S-2), (3) Channel select switch (S-3), (4) Audio volume control/ON-OFF switch (S-4), (5) Crystal ovens ON/OFF switch (S-5), (6) Filament power ON/OFF switch. There is no "delta" frequency control. Precise frequency generation and stabilization is therefore required. There is no separate band switching control. This function is accomplished by additional wafers on the channel select switch. Whenever a channel in the 2-4 MHz region is selected, the maximum power output is automatically reduced to 150 watts as required by the FCC. An additional feature is automatic selection of compatible AM on channel one. This provides a method of rapidly selecting a marine distress channel in an emergency. At present, the FCC requires all transmissions on these distress channels to be AM. Compatible AM is achieved by re-insertion of the carrier (reduced 6 db). In this manner the upper sideband (USB) and a reduced carrier are transmitted.

## RECEIVER DESIGN CONSIDERATIONS

A single-sideband, suppressed-carrier receiver must perform the following basic functions: select, amplify, demodulate and faithfully reproduce the original audio signal (figure 1). Since a SSB receiver may operate in an environment in which the desired signals vary 100 db or more, the system (front-end especially) must have a large dynamic range and a high degree of automatic gain-adjusting capability (AGC). The latter function is achieved quite differently than in an AM receiver. In the AM receiver the AGC voltage is normally derived from the carrier level. The carrier is not available in a SSB system so the AGC voltage must be developed from the audio or the intermediate frequency (IF) amplitude. This system uses the latter method. The AGC action in a SSB system must be fast enough to prevent strong signals from bursting through on the first syllable and yet not be so fast as to follow the amplitude variations of normal speech. The fast attack/slow decay AGC of this system accomplishes these objectives. Any good receiver should have a low noise figure (NF). The noise figure may be simply defined as the "amount" of noise (in excess of thermal noise) that a receiver system adds to the audio output voltage.

This receiver incorporates many MOSFETs in its design (Appendix II). The MOSFET device is relatively new to the electronics industry and has many advantages over the junction, field-effect and the bipolar transistors. The MOSFET is a voltage-controlled device that exhibits an extremely high input impedance (nominally many megohms). Unlike the junction FET, the MOSFET maintains its high input impedance without regard to input magnitude (within the maximum ratings) or polarity.

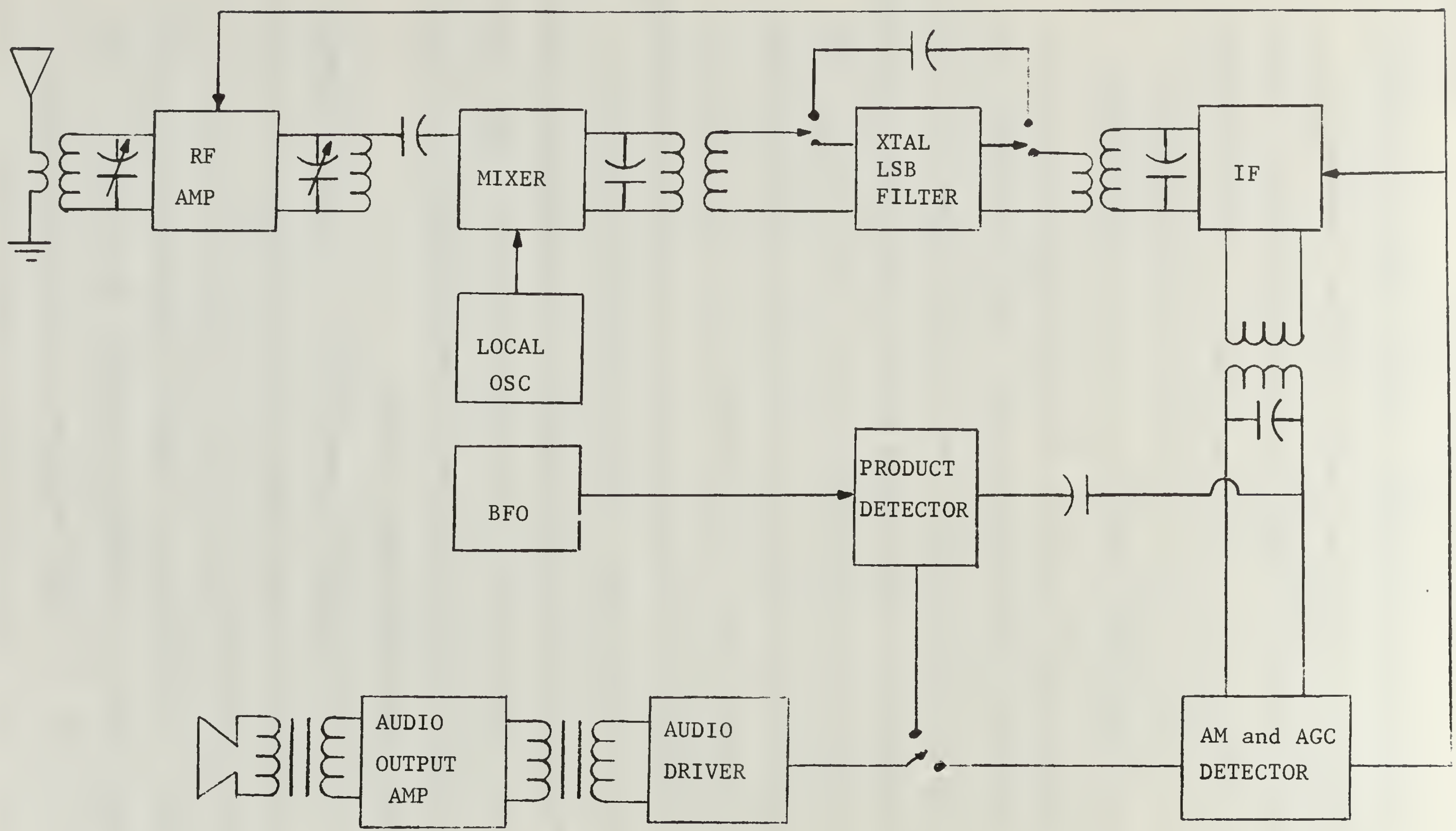



Figure 1. Receiver Block Diagram

The device has excellent power gain, a low noise figure (typically about 4 db), low feedback capacitance, excellent thermal stability and a large dynamic range. In addition, the dual-gate MOSFET exhibits excellent automatic gain control (AGC) and superior cross-modulation characteristics.

The RCA-3N140 and 3N141 are N-channel, silicon, depletion-mode, dual-gate MOSFETs which feature a series arrangement of two separate channels. Each channel is controlled by an independent gate (7). In the mixer application (3N141), each of the two inputs has its own gate and hence excellent isolation between local oscillator and signal frequency is maintained. The incoming signal is applied to gate No. 1. The mixing is unique in that the local oscillator signal applied to gate No. 2 modulates the transfer characteristic of gate No. 1. The mixing is accomplished in the quadratic region of the device transfer characteristic. Operation in a non-quadratic region of the transfer characteristic produces undesired cross-modulation effects in bipolar transistors. Cross-modulation may be defined as the modulation of a weak desired signal by a strong undesired signal.

MOSFETs have a drain-current versus gate-voltage (transfer) characteristic which is pseudo-quadratic. As such, the third-order effects and hence the cross-modulation distortion are minimal when compared with bipolar transistors (5). The RF amplifier and mixer stages are the only sections contributing to cross-modulation in this receiver since the selectivity of these two stages will sufficiently suppress the unwanted signals and render their amplitudes insignificant in succeeding stages.

It can be shown, that if a device has a transfer characteristic which is either linear or quadratic, the device gain is independent of either the desired or the undesired signal (5,10). If, however, the transfer characteristic deviates from either the linear or the quadratic form, the gain becomes a function of the amplitude of the unwanted signal. This results in cross-modulation distortion. When cross-modulation is present, no amount of selectivity following the responsible stages will eliminate the distortion since it is present in the form of modulation of the desired signal. In order to combat this undesirable effect, the unwanted, interfering signal frequencies must be suppressed by adequate pre-selection and/or minimal third-order effects in the active devices. This receiver utilizes both of these solutions in order to minimize cross-modulation distortion.

RADIO-FREQUENCY AMPLIFIER

The RF amplifier utilizes an RCA dual-gate MOSFET (3N140) in a tuned-gate, tuned-drain, self-biased configuration. This stage operates between 12 and 6.2 volts in order to provide proper AGC control by means of a negative-going dc voltage applied to gate No. 2. At zero signal, the gate No. 2 AGC potential is about 6.6 volts which providesa gate-No. 2-to-source voltage of zero volts (drain current is 4 mA). The gate-No. 1-to-source voltage is therefore -0.4 volts. Since the leakage current is negligible, a large gate-return resistor (R1) is used to preserve the high input impedance of this device.

The tuned input and output circuits are each divided into three bands: 2-4 MHz, 4-8 MHz and 8-17 MHz. The 12 channels are divided as follows; band 1: 3 channels, band 2: 5 channels and band 3: 4 channels. Each band contains one torodial coil and the indicated number of tunable, mica capacitors. All tuned circuit and antenna switching is accomplished by the channel selector switch (S-3). The unloaded Q of these resonant circuits averages greater than 100 over the entire tunable spectrum. The stage gain is about 24 db and is constant over the entire received spectrum.

## MIXER

The RF amplifier is capacitively coupled to a dual-gate MOSFET (RCA 3N141) mixer. The mixer is operated in the tuned-drain, self-biased mode. Gate No. 2 is biased at zero gate-to-source voltage in order to reduce the drain current and hence raise the working Q of the tuned output circuit. This is necessary for adequate AM selectivity. Operation in the pseudo-quadratic region of the transfer characteristic is also ensured, thereby minimumizing cross-modulation distortion as previously explained. The local oscillator injection is on gate No. 2 and is held constant at 0.7 rms,volts. Gate No. 1 is the signal injection point. The drain tuned-circuit is resonant at the mid-frequency of the crystal-filter passband (1648.5 kHz). The stepdown torodial transformer matches the high output impedance of the mixer stage to the input impedance of the crystal filter. The mixer is operated from the full 12 volts and realizes a conversion gain of about 26 db.

## CRYSTAL FILTER

The crystal filter is a Filtech Corporation device designed for a carrier frequency of 1650 kHz. In this receiver system, the local oscillator is always 1650 kHz above the desired signal and hence sideband inversion occurs. A lower sideband (LSB) filter is therefore required. The 3-db bandwidth of this filter is a nominal 2.1 kHz and a minimum carrier rejection of 25 db is advertised. The input and output impedance is 500 ohms and the filter has an insertion loss of 5 db.

The filter output impedance is matched to the impedance of the intermediate frequency (IF) amplifier section by means of a step-up, torodial transformer utilizing a tuned secondary. In the AM mode the crystal filter is bypassed and the two tuned circuits are decoupled through a small capacitor (C30). Overcoupling and a degradation in AM selectivity would otherwise result.

INTERMEDIATE-FREQUENCY AMPLIFIER

The intermediate-frequency (IF) amplifier section consists of two capacitively coupled, integrated-circuit (IC) modules (RCA CA 3002). Each is basically a differential amplifier in series with a constant-current source. By controlling the dc base voltage of this constant-current source, excellent AGC characteristics are obtained. This receiver utilizes intermediate-frequency AGC applied to the first stage. The first stage is operated at a reduced supply voltage and therefore requires a very small AGC swing to effectively control the output. The input impedance of each IC is essentially that of the input emitter follower and at the intermediate frequency of 1.65 MHz is about 100K ohms. This input impedance does not vary appreciably with AGC and hence no impedance variations are presented to the crystal filter. The output impedance is also that of an emitter follower (about 80 ohms at the IF). The IC gain is about 20 db. The total IF section gain from the primary of T-5 to the secondary of T-6 is about 70 db. In order to achieve a voltage swing of substantial magnitude for AGC purposes, an 8:1 voltage step-up transformer is provided at this point. The secondary of this torodial transformer is tuned. The AGC will be described fully in a later section.

PRODUCT DETECTOR

Thus far in the audio recovery process, the received signal has been translated to the intermediate frequency minus the audio frequency. The remaining frequency translation is down to the audio spectrum. This is accomplished by means of another dual-gate, self-biased, MOSFET (RCA 3N141) mixer. The IF (minus the audio frequencies) is mixed with the beat frequency oscillator (BFO at 1650 kHz) and the audio difference-frequency voltage is developed across a drain load resistor (R18). The radio frequencies (sum and two mixed signals) are bypassed to ground at the drain by the filter capacitor (C54).

The BFO signal is injected at gate No. 2 which is biased at +0.6 volts to improve conversion transconductance. Gate No. 1 receives its signal from the tuned secondary of the IF output transformer (T6).

AUDIO DRIVER AND OUTPUT AMPLIFIER

The audio driver utilizes another RCA integrated circuit (CA3020). This IC is a reasonably inexpensive wide-band amplifier. It is externally modified to provide excellent audio amplifier characteristics. The IC features an input buffer (emitter follower stage), built-in voltage regulator, differential amplifier, driver and Class B push-pull power output amplifier (figure 2) (8). An exceptional feature of this IC is the extremely flexible squelch capability. Squelch will be covered in a subsequent section.

The audio push-pull driver is transformer coupled to a pair of audio output, bipolar, power transistors (Q10 and Q11) which are also

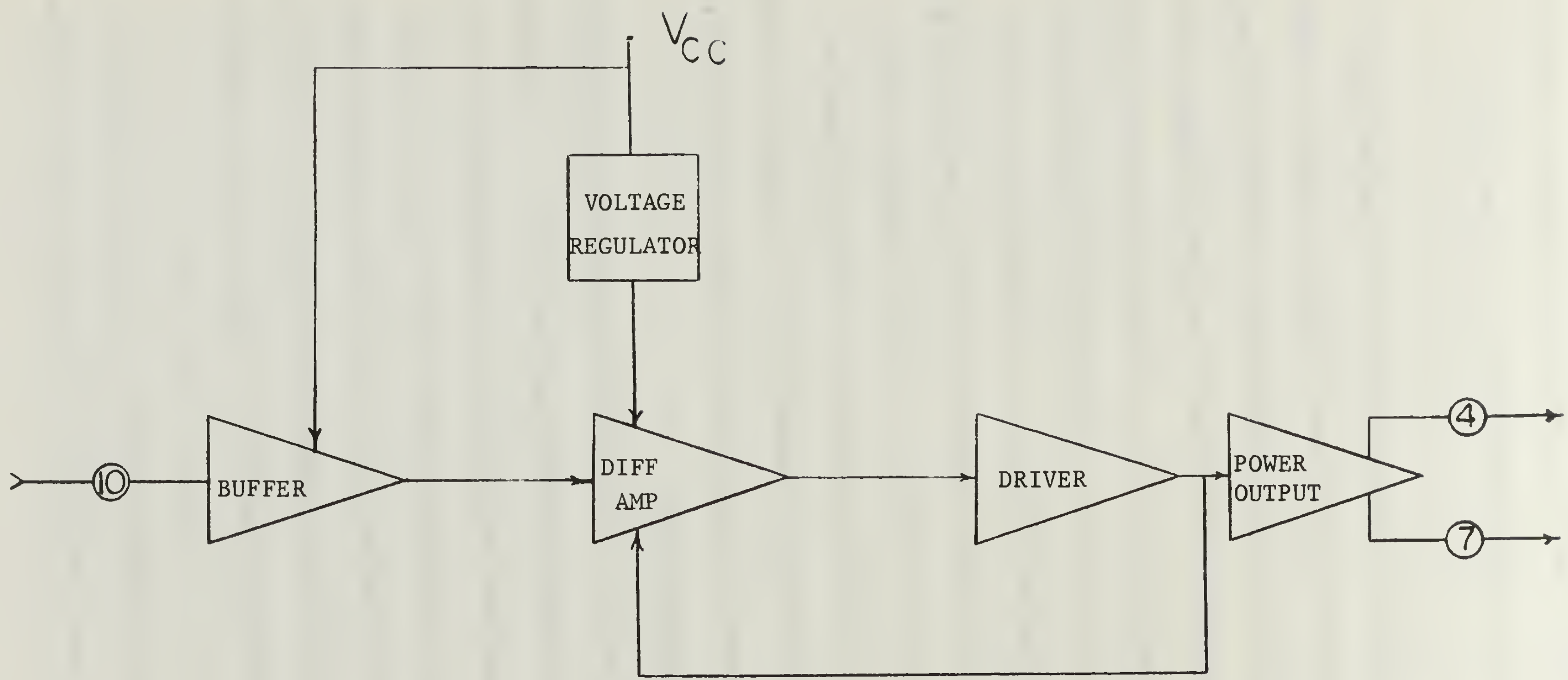



Figure 2. Audio Driver Functional Diagram

driven in the Class B push-pull mode. Push-pull is used to minimize idle current drain. Degenerative emitter feedback is incorporated to improve linearity. The audio output is transformer coupled to the panel-mounted, 4-ohm, oval speaker. Provisions are available for the incorporation of an additional low impedance speaker.

AM AND AGC DETECTOR

A germanium diode (D1) performs the functions of both an AM diode detector and an AGC detector. This is most convenient since the IF level is high at this point. The voltage developed across R12 is the detected AM envelope voltage. This voltage is also proportional to the IF level. It is in turn a measure of the incoming signal strength, hence an AGC dc reference level is established.

The AGC fast-attack time constant is set by C50 and R12 (0.5 milliseconds). The dc level is translated to the appropriate AGC levels by the AGC amplifier (Q4) and the emitter follower circuits. The slow-decay feature of the AGC network is essentially set by C55 and R19 (0.56 seconds). A Zener diode (Z1) provides the desired two-level (IF and RF) AGC reference. The AGC swings about 1.0 volt from no-signal to maximum input level. This decrease in AGC voltage holds the audio output increase to 10 db for a 94-db increase in signal input (2 microvolts to 0.1 volts). The AGC threshold is at 4 microvolts input voltage.

SQUELCH

The squelch circuit is essentially a transistor switch (Q9) controlled by both a manual set-level and an automatic break-out amplifier (Q7). Transistor Q8 provides a constant-current source. R25 manually sets the threshold of the transistor switch. When this transistor (Q9) saturates, the differential-amplifier voltage supply in the audio driver (IC3) is clamped to 0.3 volt (relative). This cuts off the audio driver. Break-out is achieved by amplification of the RF-AGC fluctuation, using the PNP squelch amplifier (Q7). When the transistor switch is cut off, the audio driver functions normally.

INTERNAL POWER DISTRIBUTION

The receiver section requires a 12-volt power input. It idles at 50 mA, but draws as much as 600 mA for maximum audio output levels. The IF section requires a nearly equal and well regulated fraction of this 12-volt supply. A method is also required to allow the RF-AGC voltage to swing negative (relative). The RF amplifier is therefore operated between 12 and 6.2 volts and the IF amplifier is operated between 12 volts and ground, with a 6.2-volt reference. For proper squelch action, the audio driver is also operated between 12 and 6.2 volts. However, the current requirement of the audio driver (IC3) varies so widely with output power that a separate, Zener-diode controlled, 6.2-volt, dc buss is utilized (figure 3). All supply voltage to the receiver is removed when the press-to-talk relay (S-1) is in the transmit position.

The oscillator section must have exceptionally good frequency stability. If the oscillators were operated from the main dc supply voltage, frequency "pulling" would result from small variations in the voltage supply caused by rapid or extreme current demands. In order to provide a well regulated oscillator power supply, a separate 9.1-volt buss is established on the oscillator circuit board, using a Zener diode.

OSCILLATOR SECTION

This is the only portion of the transceiver that is common to both the receiver and to the transmitter. The simplex oscillator

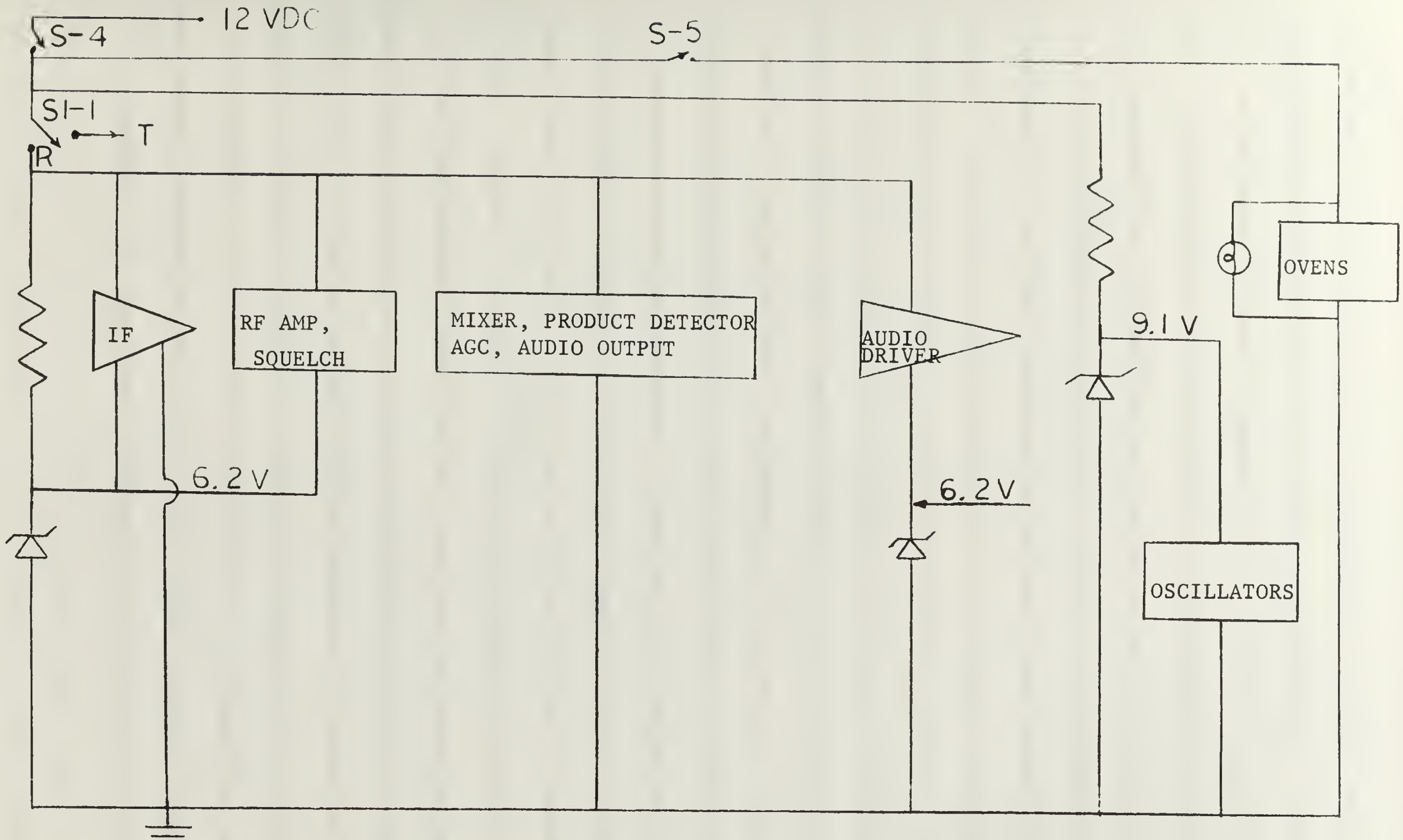



Figure 3. Internal Power Distribution

supplies the local oscillator frequency to the receiver on <u>all</u> channels and to the transmitter on simplex (1,2,4,5,6,9 and 10) channels. The semiduplex oscillator supplies the transmitter on semiduplex (3,7,8,11 and 12) channels. Simplex operation is defined as transmission and reception on the same frequency. Semiduplex operation is defined as reception on one frequency and transmission on another. This mode is necessary for communication with many public correspondence stations. If simplex operation is desired on a semiduplex channel, the correct transmitter frequency crystal must also be inserted in the semiduplex oscillator. This is the penalty for the increased versatility of semiduplex operation. The beat frequency oscillator (BFO) supplies both the receiver and the transmitter. In the AM mode, the BFO is off when the press-to-talk relay is in the receive position.

Continuing with the theme of superior performance through "state of the art" theory and devices, a single-gate MOSFET is employed in each of the three oscillators. Due to its small mass, an FET reaches thermal equilibrium in a matter of seconds. The low operating potential and small current requirements of this device result in low power dissipation and hence low radiated thermal energy. The net result is a cooler and more stable circuit (4). The MOSFET used (RCA 40468) operates very well in the Pierce-type crystal oscillator configuration. Snap-action crystal ovens are employed to minimize frequency drift due to temperature variations. These ovens maintain the crystals at 65 degrees Centigrade (± 3 degrees).

The output amplitude from this type of crystal oscillator varies widely with frequency and also to some extent with crystals of the same frequency. Thus output-level stabilization is required since receiver performance depends upon an oscillator injection which is within definite amplitude limits. The simplex and semi-duplex oscillators each employ a diode limiter and a bipolar transistor amplifier. The load resistor of each amplifier is a potentiometer from which the required injection levels are extracted. The "off" oscillator is prevented from loading the "on" oscillator by wafer switching.

Below 2 MHz, the operation of this oscillator configuration is marginal. Since the BFO operates at a frequency of 1650 kHz, a capacitive voltage divider is required across its crystal. The BFO employs a different type output-level adjustment. A series-resonant circuit provides this adjustment. A limiter is not required since the crystal-to-crystal variation at this frequency is not large.

## SWITCHING

The requirement to simplify the operation of, and to provide common circuitry for, this transceiver has introduced the necessity for a somewhat complicated switching arrangement. This is the internal complexity required to achieve external simplicity. The switching requirements of the receiver are divided into three areas: (a) Channel selection (S-3), (b) Signal flow and automatic AM (S-2 and S-3), (c) Oscillator switching (S-1 and S-3). The transceiver transmit button controls the press-to-talk relay (S-1). This relay switches the antenna from the receiver to the transmitter and also deprives the receiver of 12-volt power when the transmitter is keyed. The relay is also required in the oscillator section for semiduplex operation. The latter function will be fully described in the oscillator switching section.

CHANNEL SELECTION

Five wafers on the channel selector switch (S-3), adjust the antenna and the RF-amplifier tuned circuits. The entire 2-17 MHz spectrum is covered by variable,mica capacitors in parallel with one of the three fixed, torodial coils (T-1,2,3 and L-1,2,3). Even though the input impedance of the RF-amplifier stage is about one megohm, an attempt is made to match the antenna impedance (nominally 52 ohms). A very large turns ratio is required. However, the largest of the toroid secondaries (33 uH) has only 75 turns. A minimum of two primary (antenna side) turns was selected, from considerations of coupling. This minimum is used for each input transformer, recognizing that some antenna mismatch results.

Wafer S3-A1 connects the antenna to the proper matching transformer (figure 4). S3-A3 selects the proper band and S3-A2 selects the proper tuning capacitor. The RF-amplifier-output switching wafers, S3-R1 and S3-R2, function in the same manner as S3-A3 and S3-A2 respectively. All of these wafers are of the twelve-position, single-pole, non-shorting type.

SIGNAL FLOW AND AUTOMATIC AM

The mode switch (S-2) accomplishes basic signal-flow switching. In order to provide automatic AM on channel one, parallel ("OR" logic) switching is required (figure 5). On all channels except channel one, S3-D1, S3-F1 and S3-F2 are closed, and the mode switch (S-2) selects

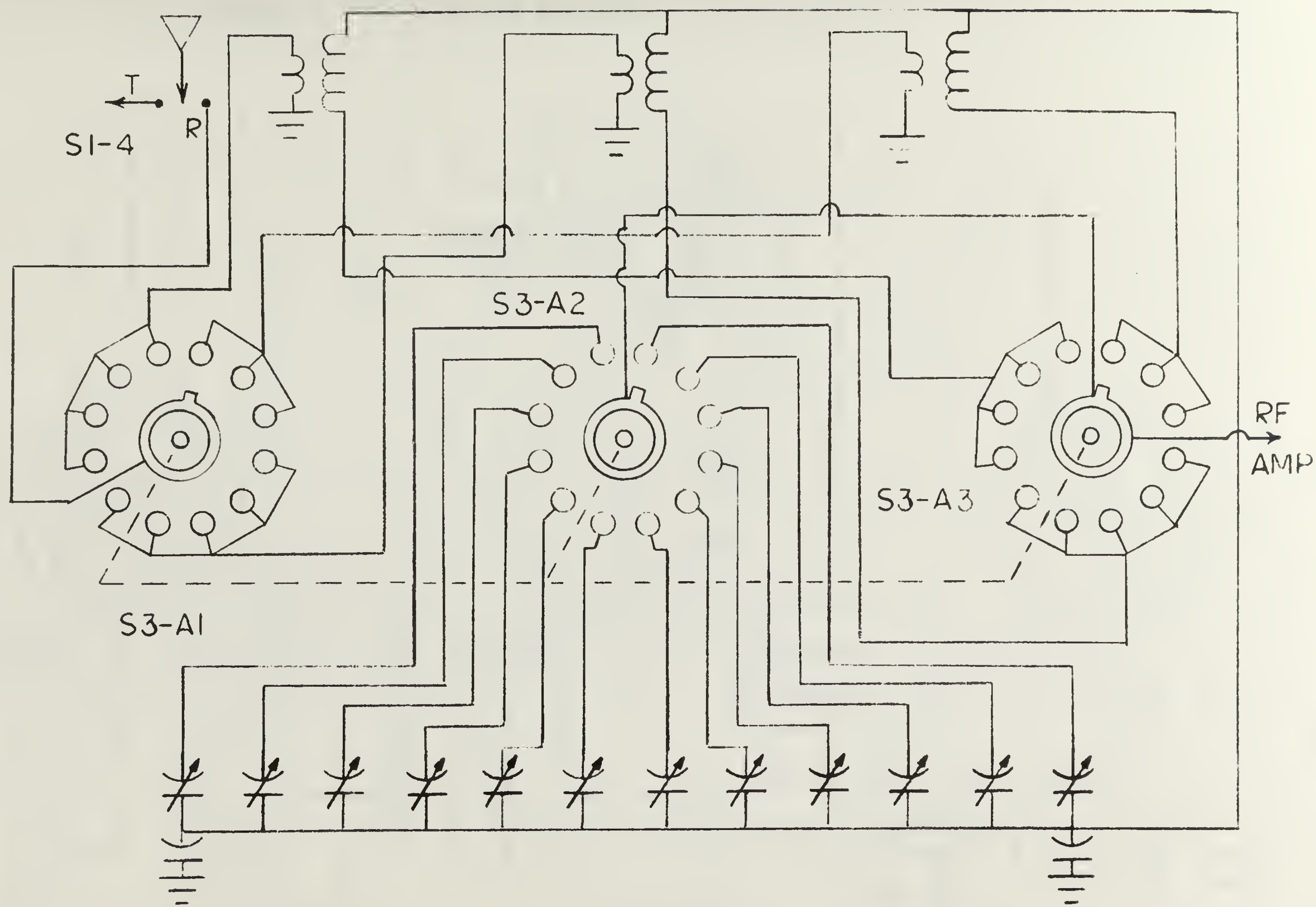



Figure 4. RF Amplifier Input Switching

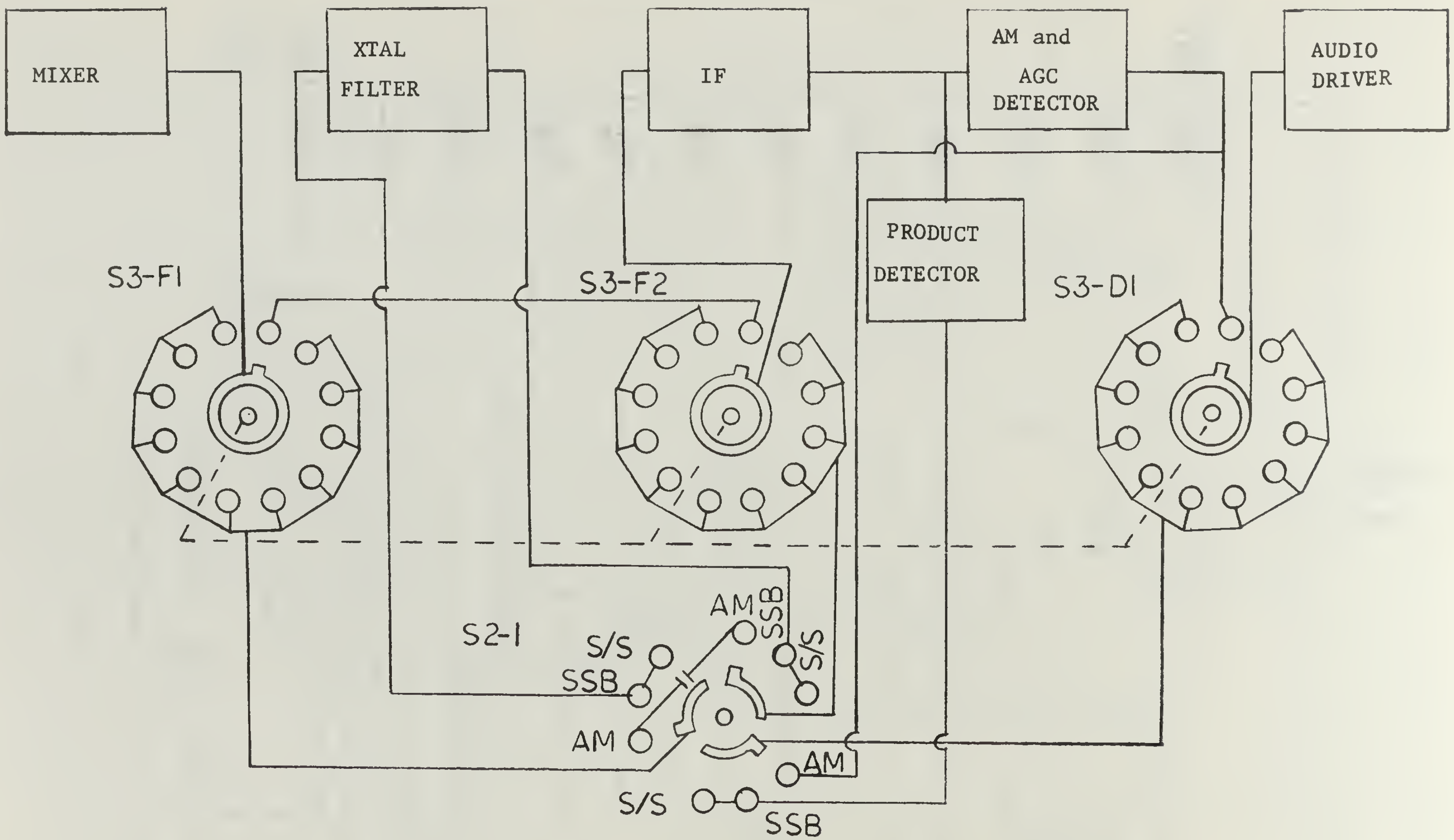



Figure 5. Automatic AM Switching

the signal-flow path. The automatic AM feature requires bypassing of the mode switch functions on channel one. Each signal-flow switching function must be bypassed and hence a total of three, twelve-position, single-pole, non-shorting wafers are required. The mode selector (S-2) wafers consist of three separate sections. Each section contains a three-position, single-pole switch. Three sections (one wafer) are required for the signal-flow switching.

OSCILLATOR SWITCHING

Local oscillator switching distributes the output of the simplex and the semiduplex oscillators (figure 6). Four, twelve-position, single-pole wafers on the channel selector switch (S-3), and one position on the press-to-talk relay (S-1) are required. S3-01 selects the proper simplex oscillator crystal and S3-03 selects the proper semiduplex oscillator crystal. Positions 3,7,8,11 and 12 are required on this wafer. S3-02 prevents the "off" oscillator from the loading the "on" oscillator. S3-04 and S-1 select the proper oscillator during semiduplex operation by controlling the drain voltage supply. The simplex oscillator functions whenever simplex operation is selected (7 channels) or when semiduplex operation is selected and the press-to-talk button is not depressed (i.e., receiver operation). In order to supply drain voltage to the semiduplex oscillator, semiduplex operation (any one of 5 channels) must be selected and the press-to-talk button must be depressed (i.e., transmitter operation).

The BFO is required by the receiver whenever either the SSB or S/S mode is selected. This oscillator must be off whenever receiving AM, due to undesirable oscillator feed-through to the AM detector from gate 2 to gate 1 of the product detector (Q3). The automatic

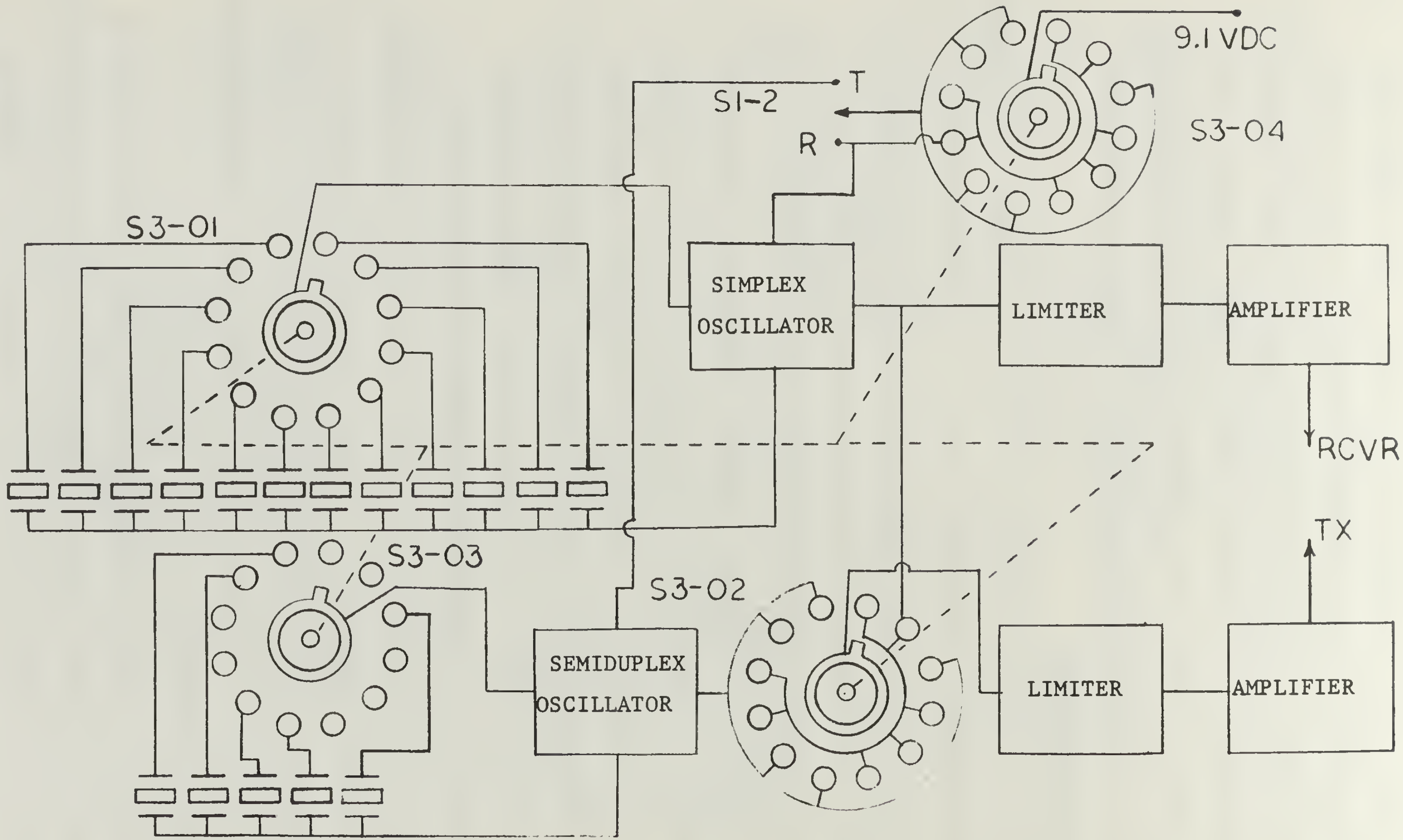



Figure 6. Oscillator Switching

AM feature of channel one increases the switching complexity (figure 7). Another twelve-position, single-pole wafer (S3-B1) is required on the channel selector switch. The transmitter always requires the BFO and hence a logical "not receive" (i.e., transmit) bypass must be provided for the BFO drain voltage supply. The press-to-talk button (S-1) provides this path.

## RECEIVER TESTING

In order to properly evaluate the receiver performance, several tests were conducted. There are unfortunately no universally accepted methods for measurement of receiver characteristics. The test conditions therefore must be completely specified so that the results may be correctly evaluated. In general, the receiver testing outlined in reference (6) is followed.

### SENSITIVITY

The sensitivity of a receiver indicates its ability to receive, demodulate and reproduce weak signals with a prescribed degree of intelligibility. The test setup in figure 8 outlines the procedure. The output impedance of the RF signal generator is the same as that of the assumed antenna (50 ohms). The signal generator (URM-26B) provides an rms-output microvoltmeter and this was used to indicate the level of signal input to the receiver. The rms-audio output was recorded (in db) for zero RF-signal input. This is an indication of the total signal generator (antenna) and receiver noise. The rms input was then increased until a 10-db increase in audio output was observed. The rms value of the RF input voltage was recorded. This is the sensitivity of the receiver. For SSB the input CW signal was adjusted

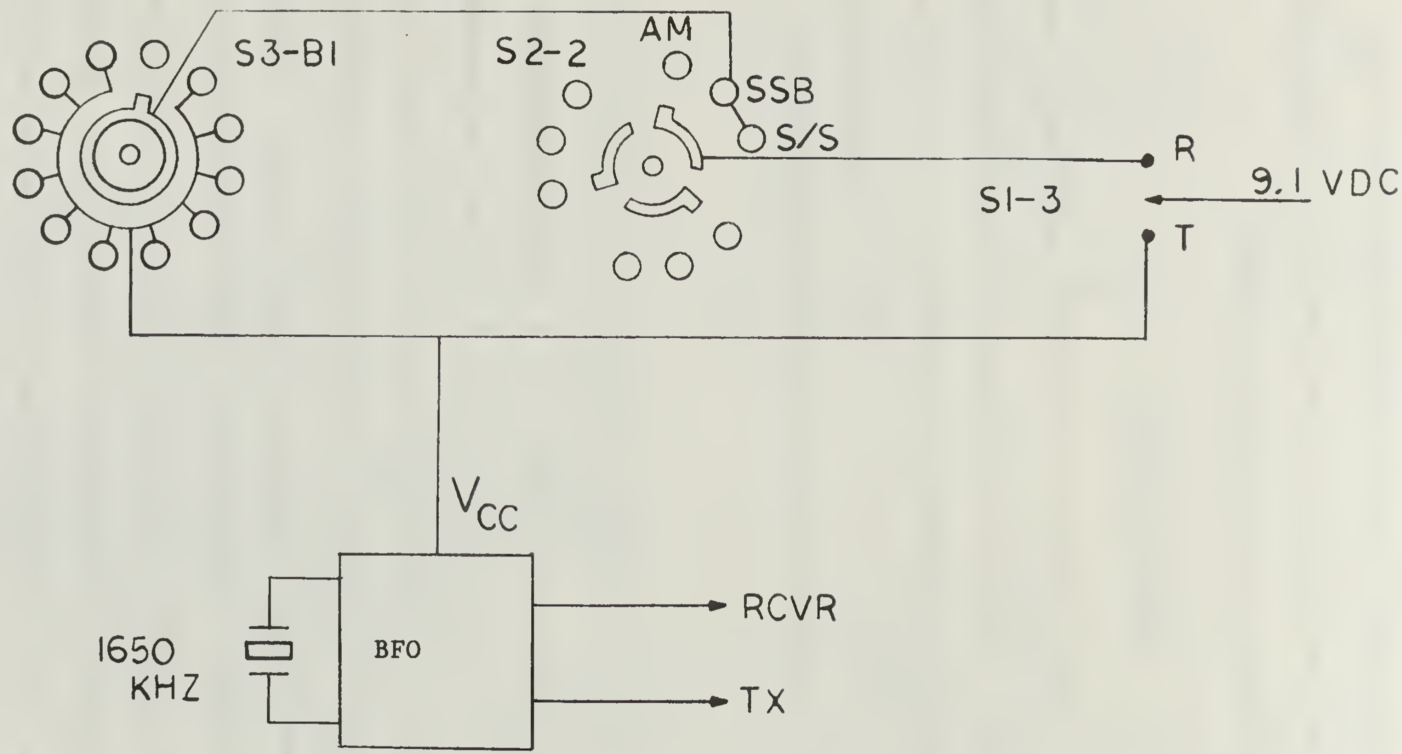
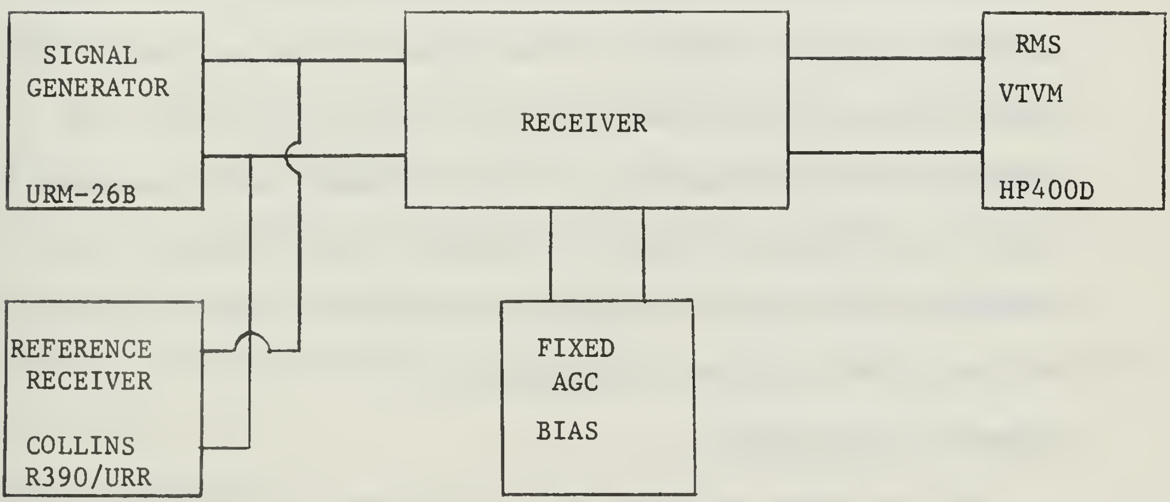



Figure 7. BFO Switching


SENSITIVITY, IMAGE REJECTION, AGC, SQUELCH




AM SELECTIVITY

Figure 8

for a 1-kHz, audio-output beat frequency. For AM the input frequency was modulated 30% at 1 kHz. The results of this test are recorded in Appendix III. The receiver is well within sensitivity specifications on all test frequencies and modes.

## SELECTIVITY

The selectivity of a receiver is a measure of its ability to respond to a desired signal while discriminating against an unwanted signal of nearly the same frequency. In the SSB or S/S mode the receiver selectivity is essentially that of the crystal filter and hence the 3 db bandwidth is a nominal 2.1 kHz.

In order to measure the AM selectivity, the AGC voltage was externally supplied by a fixed bias supply. The test setup is shown in figure 8. A reference receiver (Collins Radio Company R-390/URR) was used to accurately establish the input frequency. The signal generator supplied a 30%, AM, 1-kHz signal to the receivers. The signal frequency was varied above and below the prescribed test frequency and the frequencies at which the audio output was down 3, 6 and 12-db relative to the test frequency were recorded. This procedure established the overall (RF and audio) receiver selectivity. The results are tabulated in Appendix III.

## AUTOMATIC GAIN CONTROL

The AGC action was measured by injecting a CW signal at the lowest detectable RF level (figure 8). The input level was increased at selected increments until a large signal level was reached (0.1 rms volts-maximum output for the URM-26B). The audio output change (in db) was recorded for each RF input level. The AGC voltage was initially monitored to determine what input level caused the AGC line to begin a dc change. This RF input level is the AGC threshold. The results are plotted in Appendix III. The AGC characteristic is fast attack/slow decay and is established by circuit time constants.

SPURIOUS RESPONSES

Many types of spurious responses are possible in a superheterodyne receiver. Of particular importance is the image response. This occurs when a signal of frequency equal to the signal frequency plus twice the IF is available at the mixer input. This combination produces the intermediate frequency (difference mixing). Since this is generally the most troublesome spurious response, it was the only one investigated in detail. The test setup in figure 8 was utilized in the following manner. An audio reference level was established at the signal frequency and the input level was noted. The signal generator was then tuned to the image frequency and the RF input increased until the previous audio level was reached. The ratio of RF input levels was computed (in db). This procedure was repeated for various frequencies throughout the receiver passband. As could be expected, image rejection decreased as the ratio of intermediate frequency to signal frequency decreased (9). The results are tabulated in Appendix III.

SQUELCH CONTROL

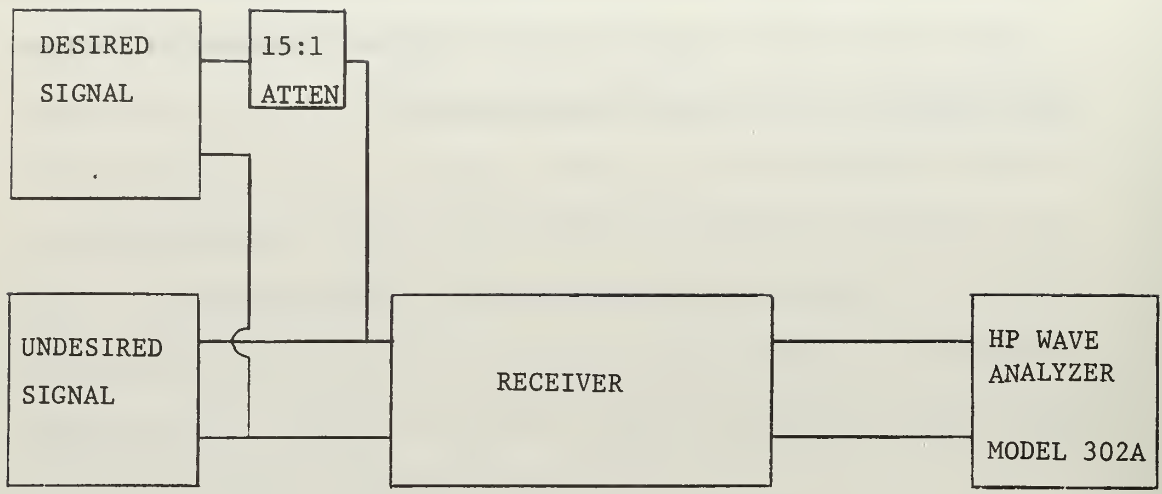
The squelch circuitry sets the receiver signal threshold by suppressing the noise output when no transmissions are being received. It must, however, allow the receiver to rapidly respond to an incoming signal whenever it rises above this threshold. The threshold is manually set by the Squelch Control (R25). The normal adjustment is such that the ambient noise output is barely audible. The test setup in figure 8 was used to determine the increase in signal strength required to produce various increases in audio output. The test was repeated for several initial "noise" levels. These levels were simulated by adjusting the signal generator for the indicated thresholds (Appendix III). The audio output was then squelched until it was barely audible. This audio output was noted and used for each test. The signal generator output was increased until 3, 6 and 10-db increases were noted in the receiver audio output. The input-signal increase required to produce each of these increases in audio output is recorded in Appendix III.

CROSS-MODULATION DISTORTION

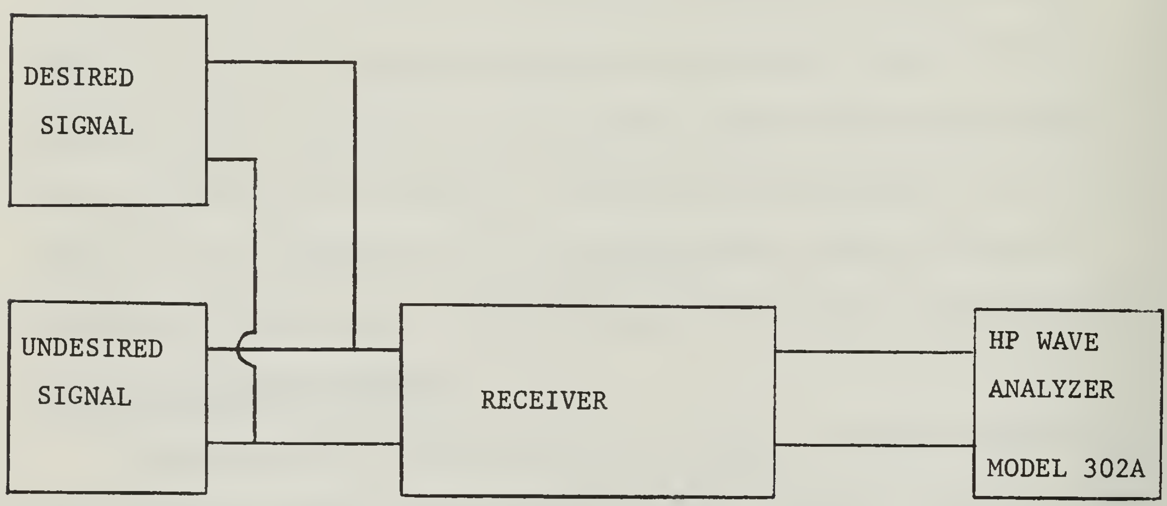
The cross-modulation (CM) characteristics were measured using the test setup shown in figure 9. The desired signal (CW) was tuned to the middle of the filter passband. The undesired signal was tuned outside the filter passband and amplitude-modulated 30% at 1 kHz. Using an audio wave analyzer (Hewlett-Packard Model 302A), various CM ratios were observed and the undesired signal amplitude required to achieve each was recorded. The CM ratio is defined as the ratio (in db) of the amplitude of the undesired audio output to that of the desired audio output. The results are recorded in Appendix III.

INTERMODULATION DISTORTION

Intermodulation (IM) distortion is present whenever third-order non-linearities exist in any receiver stage. Given a two-tone signal input, the IM products are of the form: $2f_2 - f_1$, $2f_1 - f_2$, etc. The test setup is shown in figure 9. Both signal generators were tuned (CW) so that they produced audio output beats of equal amplitudes but of slightly different audio frequencies. The ratio of the amplitude of either audio output frequency to that of the in-band distortion term (in db) was determined with the audio wave analyzer. This ratio is the IM distortion of the receiver. The test results for various test frequencies are listed in Appendix III.




CROSS-MODULATION DISTORTION




INTERMODULATION DISTORTION

Figure 9

## BIBLIOGRAPHY


1. Collins Radio Company, Fundamentals of Single Sideband, Cedar Rapids, Iowa: Collins Radio Company, 1959.

2. Federal Communications Commission 32nd Annual Report for the Fiscal Year 1966, Washington: U. S. Government Printing Office, 1966.

3. Federal Communications Commission Rules and Regulations, Vol. IV, Parts 81 and 83, Washington: U. S. Government Printing Office, 1964.

4. Hanchett, G. D., "Insulated-Gate Field Effect Transistors in Oscillator Circuits", Radio Corporation of America Publication No. ST-3520, August 1967.

5. McKeon, E. F., "Cross-Modulation Effects in Single-Gate and Dual-Gate MOS Field Effect Transistors", Radio Corporation of America Application Note AN-3435, August 1967.

6. Pappenfus, E. W., Bruene, W. B., and Schoenike, E. O., Single Sideband Principles and Circuits, New York: McGraw-Hill Book Company, 1964.

7. Radio Corporation of America, "Technical Data Sheet for the 3N140 and 3N141", August 1967.

8. Sanquini, R. L. and Keller, J. P., "Application of the RCA-CA 3020 Multi-Purpose Integrated-Circuit Wide-Band Power Amplifier", Radio Corporation of America Integrated Circuits Application Note ICAN-5320, August 1967.

9. Sturley, R. L., Radio Receiver Design, London: Chapman and Hall LTD, 1947

10. Terman, F. E., Electronic and Radio Engineering, New York: McGraw-Hill Book Company, 1955.

## APPENDIX I

### COMPARISON OF SSB and AM SYSTEMS
(Equal S/N ratios)

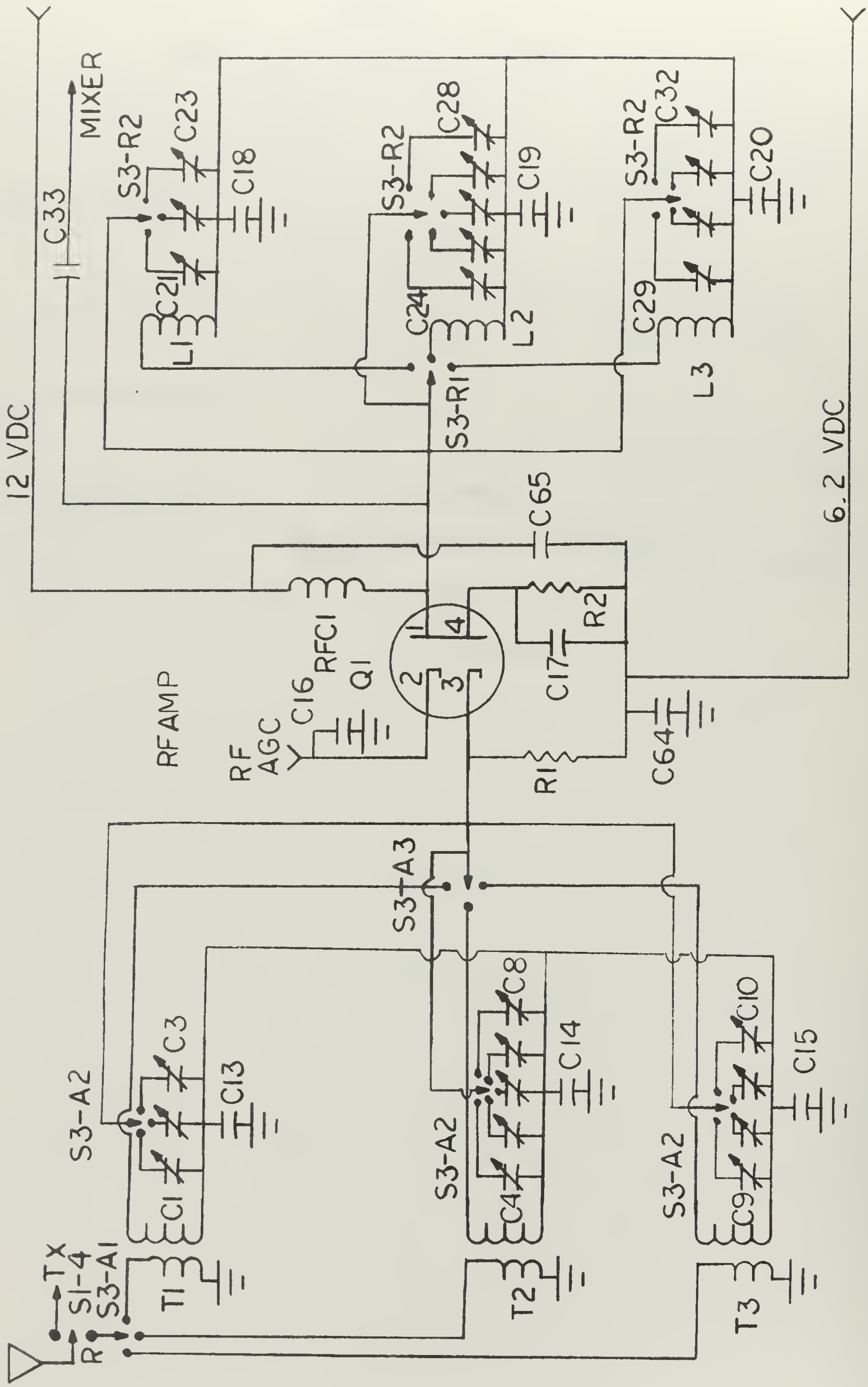
| | AM | SSB |
|---|---|---|
| RADIATED RF POWER | 1.5 watts (0.25 watts in each sideband) | 0.5 watts |
| RF ENVELOPE | 4 watts, peak<br>2 volts, peak | 0.5 watts, peak<br>0.7 volts, peak |
| PEAK DETECTED AUDIO VOLTAGE | 1 volt | 0.7 volts |
| RELATIVE NOISE-VOLTAGE IN EACH RECEIVER | $NF\sqrt{B_{AM}}$ | $NF\sqrt{B_{SSB}} = 0.7NF\sqrt{B_{AM}}$ |
| S/N VOLTAGE RATIO | $\frac{1}{NF\sqrt{B_{AM}}}$ | $\frac{0.7}{0.7NF\sqrt{B_{AM}}} = \frac{1}{NF\sqrt{B_{AM}}}$ |

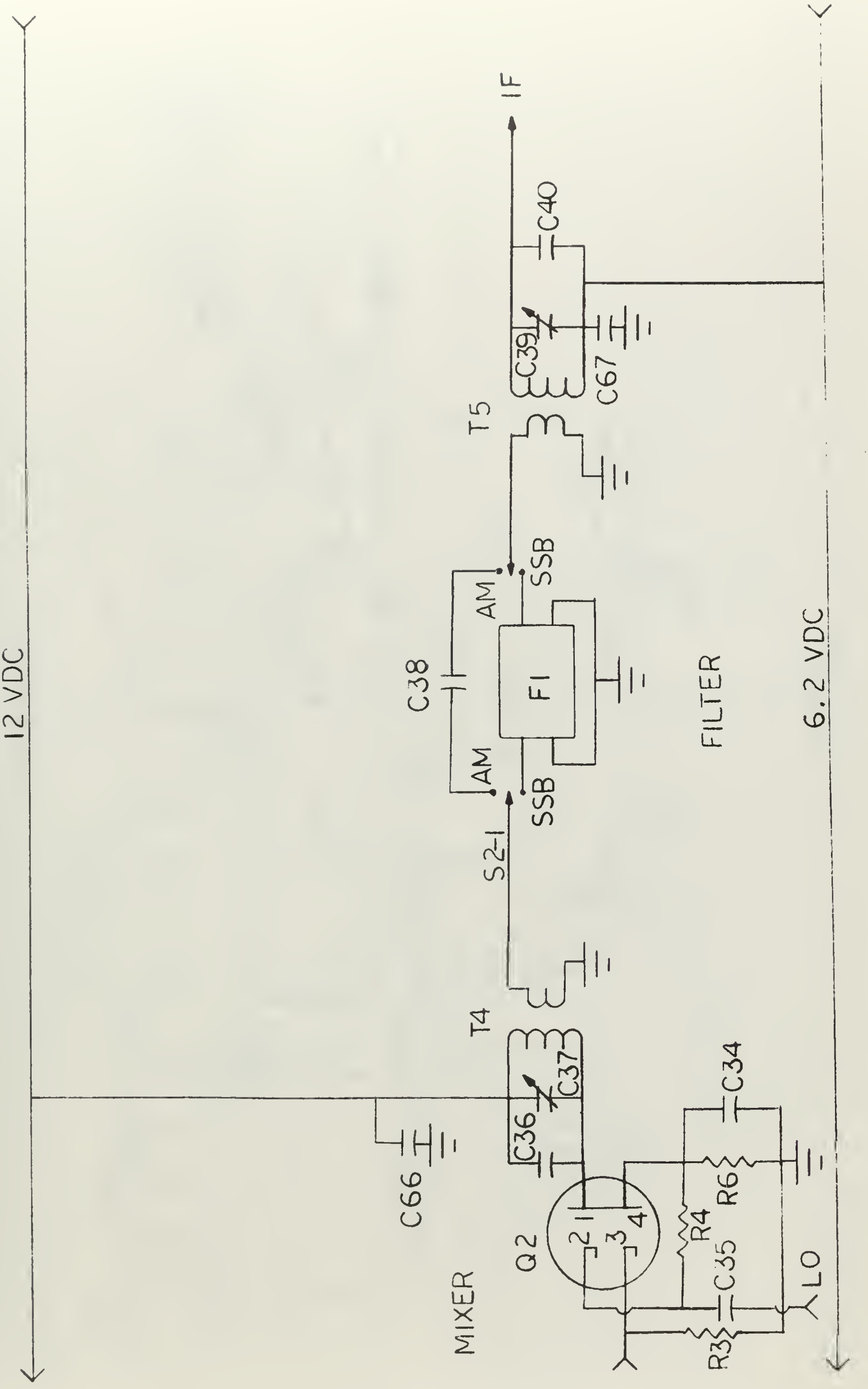
Appendix II

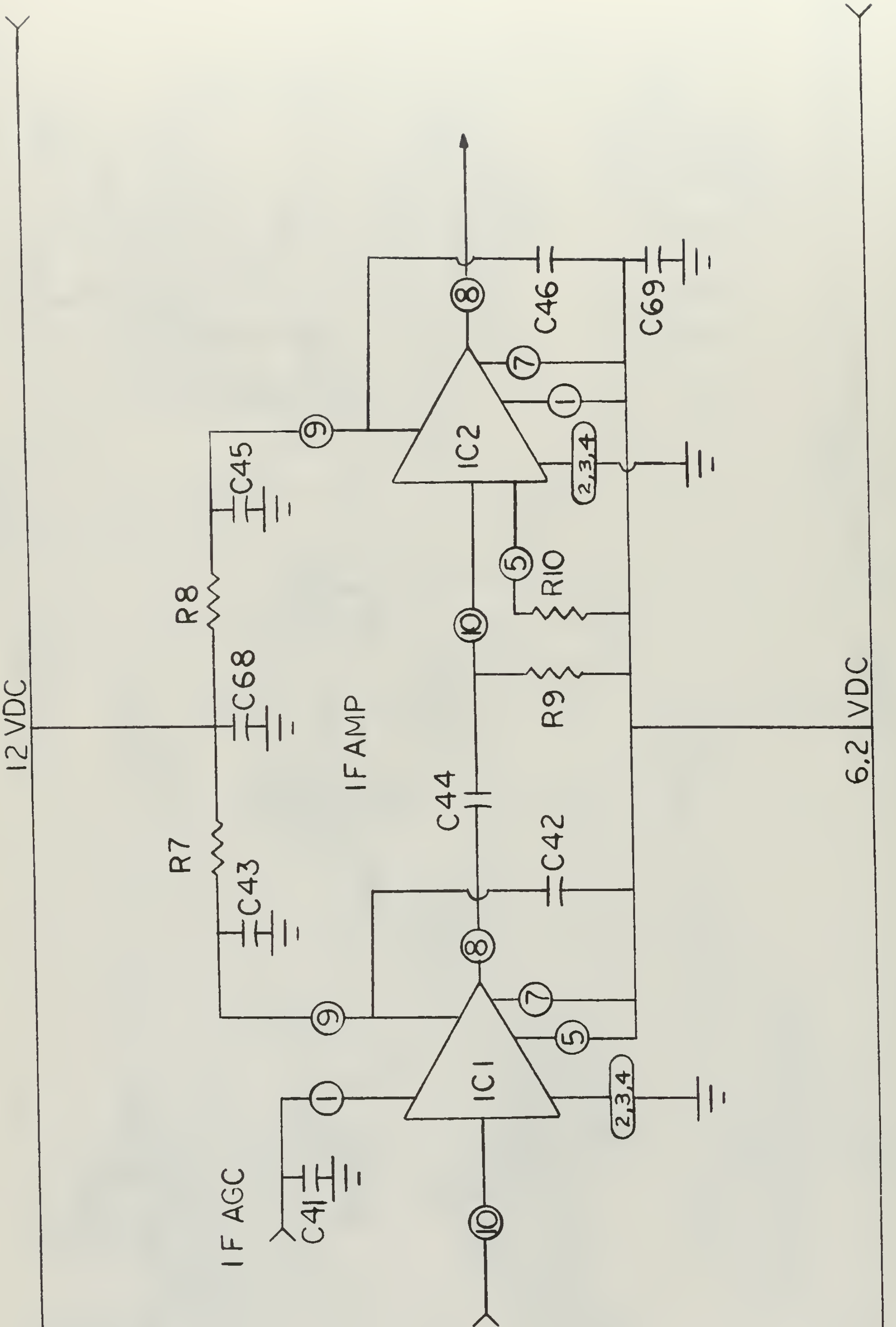
Receiver Schematic Diagram

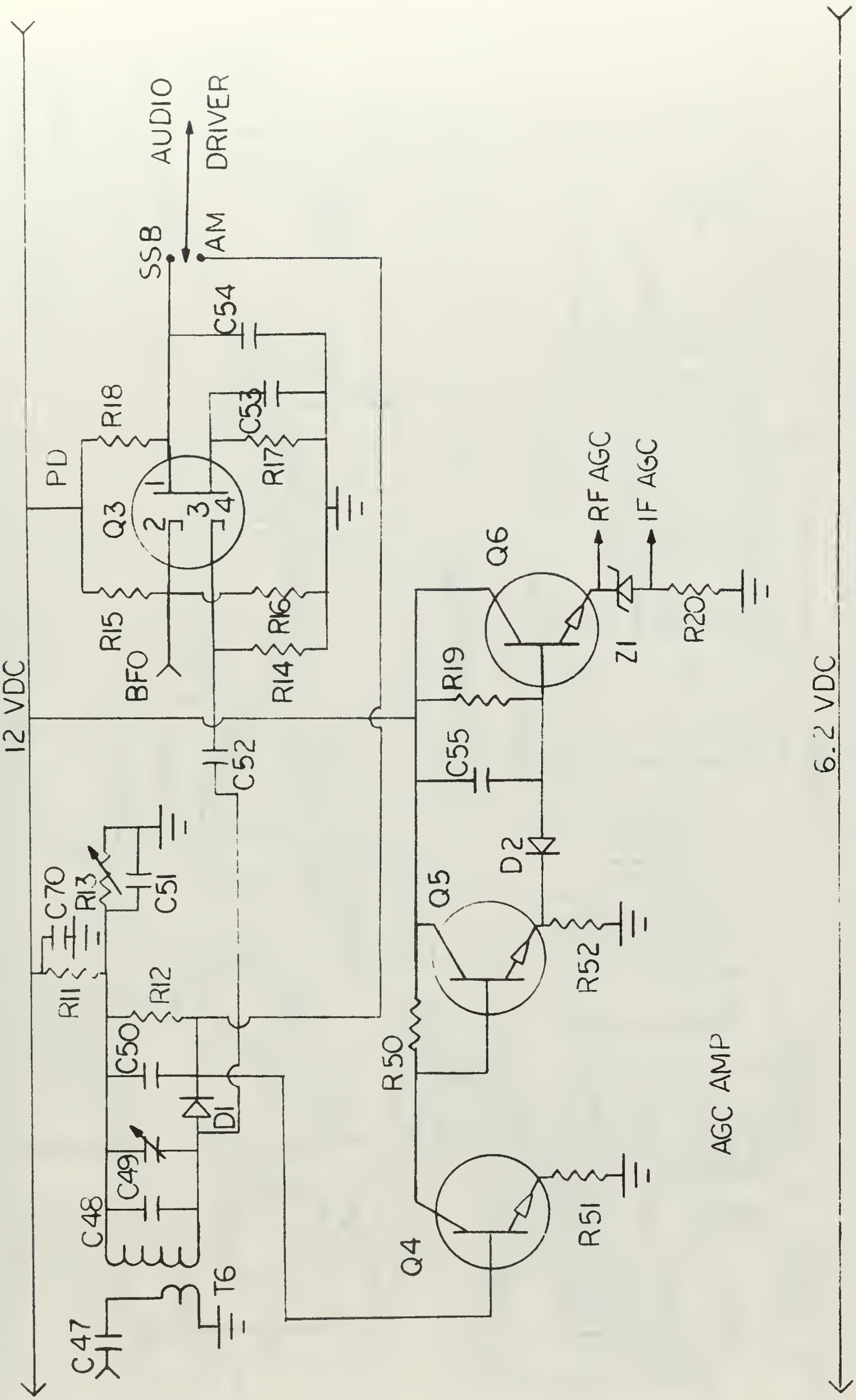
and

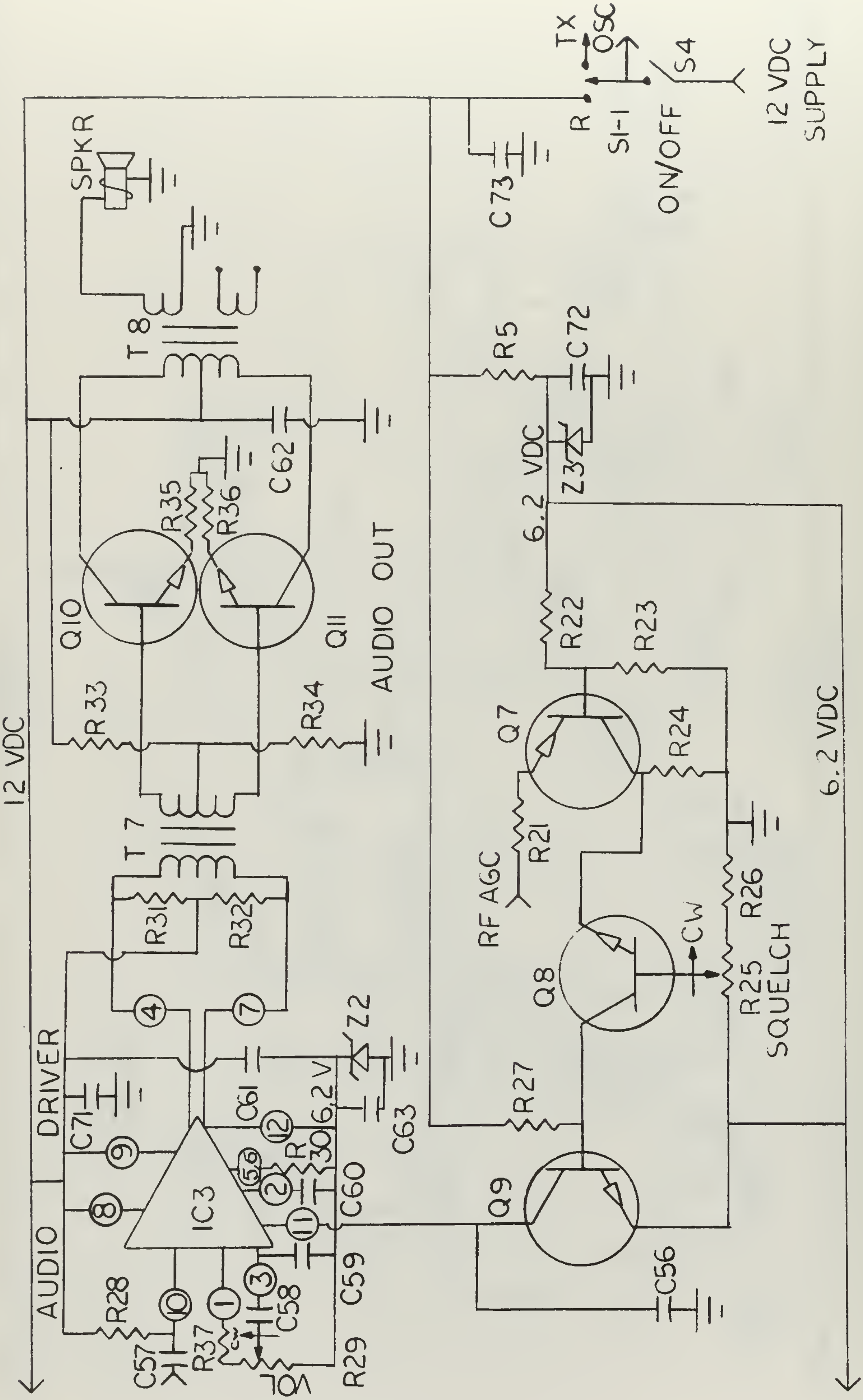
Component List

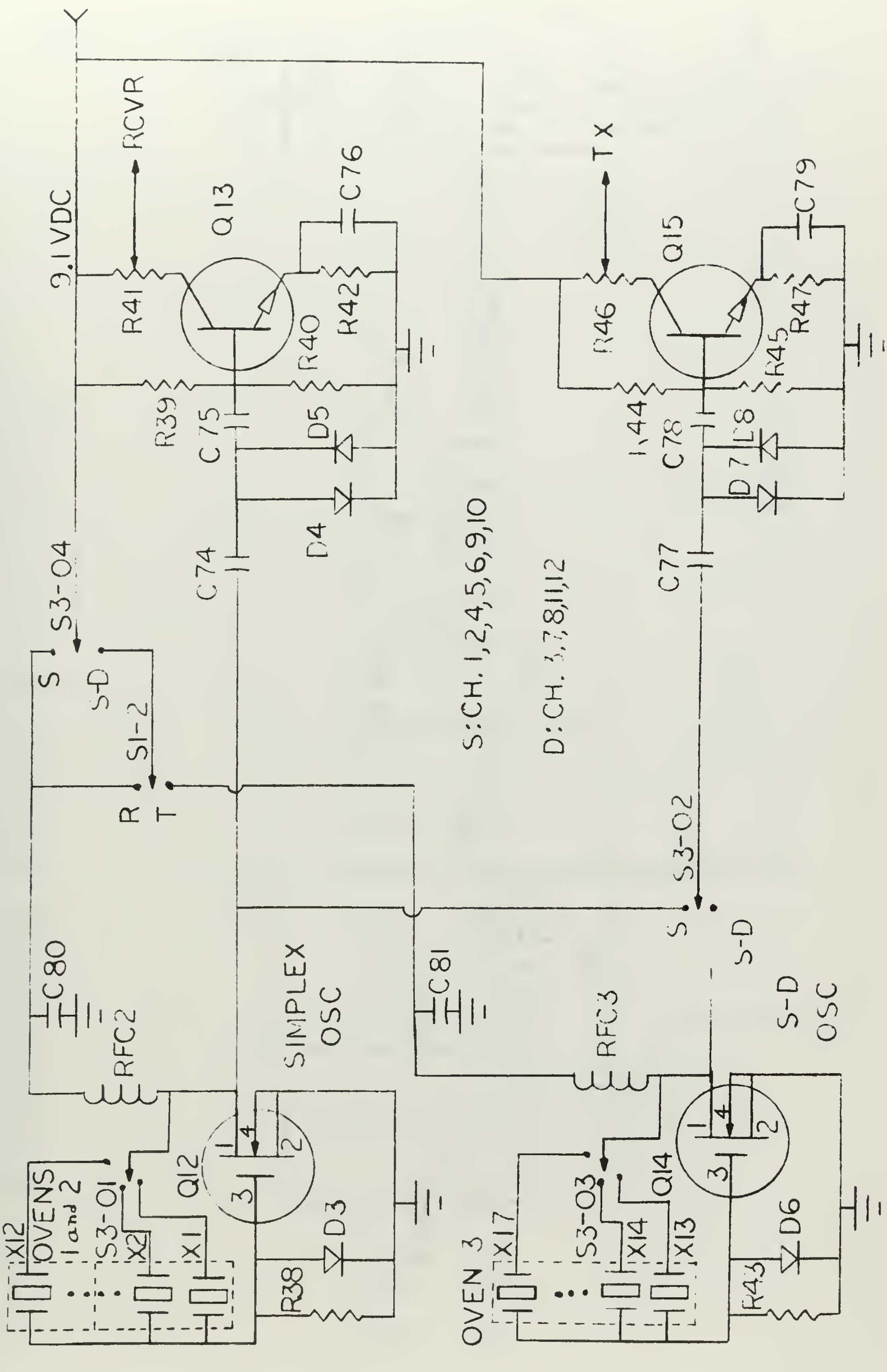

RF AMP
RF
AGC
C16
RFC1
Q1
12 VDC
6.2 VDC
C33
MIXER
S3-R2
C23
C18
C21
L1
C24
C28
C19
L2
S3-R1
C29
C32
C20
L3
C65
R2
C17
C64
R1
S3-A3
S3-A2
C3
C13
C1
C8
C14
C4
C10
C15
C9
TX
S1-4
S3-A1
R
T1
T2
T3

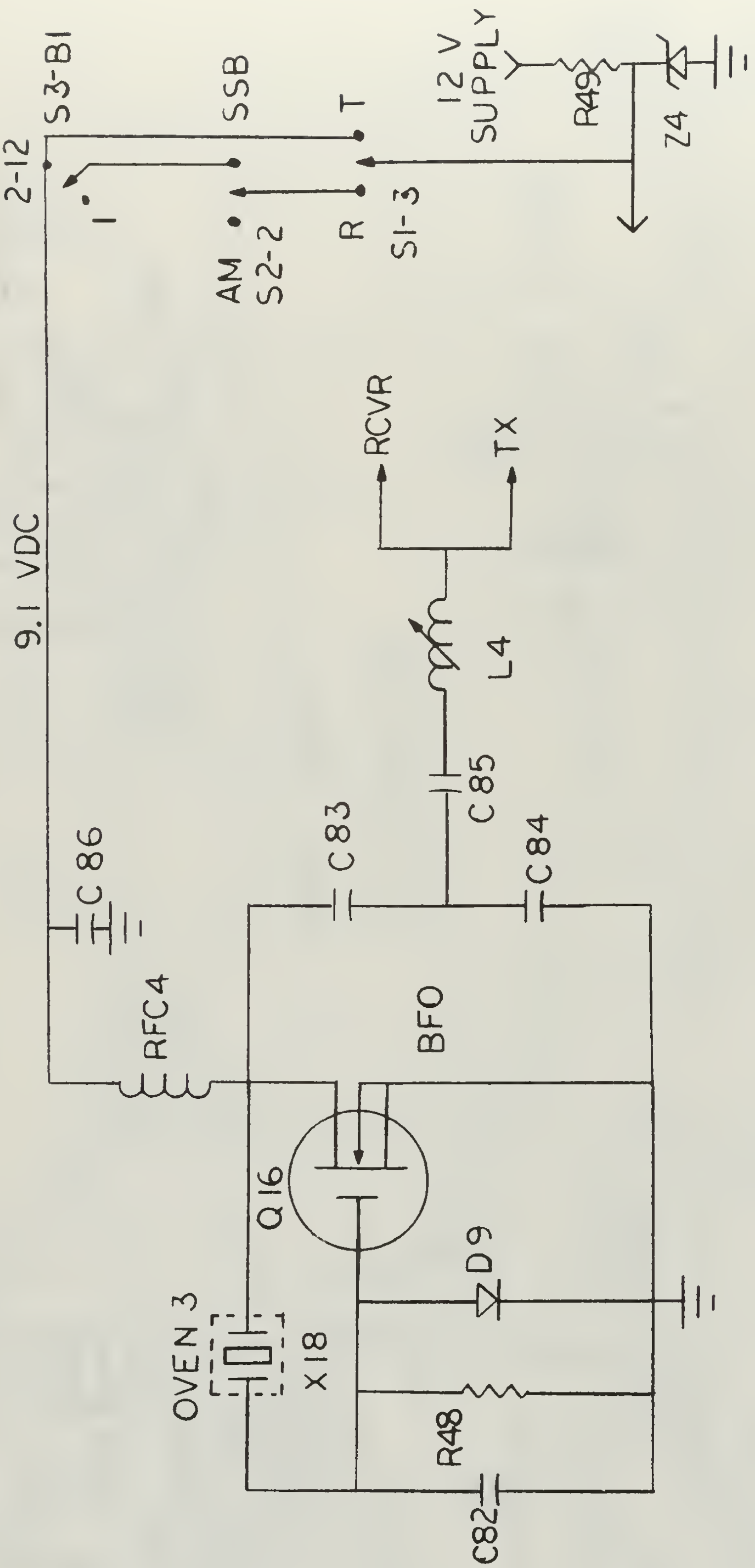

12 VDC
MIXER
Q2
C66
C36
C37
T4
R3
C35
R4
R6
C34
LO
S2-1
AM
SSB
C38
F1
FILTER
AM
SSB
T5
C39
C67
C40
IF
6.2 VDC


12 VDC
6.2 VDC
IF AMP
IF AGC
IC1
IC2
R7
R8
R9
R10
C41
C42
C43
C44
C45
C46
C68
C69
1
2,3,4
5
7
8
9
10


12 VDC
6.2 VDC
AGC AMP
AUDIO DRIVER
SSB
AM
PD
Q3
R18
C53
C54
R17
R15
R16
R14
BFO
C52
C70
R13
C51
R11
R12
C50
C49
C48
D1
T6
C47
Q4
Q5
Q6
R50
R51
R52
D2
C55
R19
RF AGC
IF AGC
Z1
R20


12 VDC
AUDIO
DRIVER
IC3
R28
C57
R37
VOL
C58
C59
R29
C60
R30
6.2 V
C61
C63
C71
Z2
T 7
R31
R32
R 33
R34
Q10
Q11
R35
R36
C62
T 8
SPKR
AUDIO OUT
Q9
C56
R27
Q8
CW
R25
SQUELCH
R26
RF AGC
R21
Q7
R24
R23
R22
6.2 VDC
Z3
R5
C72
C73
R
SI-I
ON/OFF
TX
OSC
S4
12 VDC
SUPPLY


9.1 VDC
RCVR
R41
Q13
C76
R42
R40
R39
C75
D5
D4
C74
S3-04
S
S-D
S1-2
R
T
S:CH. 1,2,4,5,6,9,10
D:CH. 3,7,8,11,12
TX
Q15
C79
R46
R47
R45
R44
C78
D8
D7
C77
S3-02
S
S-D
C80
RFC2
SIMPLEX
OSC
C81
RFC3
S-D
OSC
OVENS
1 and 2
X12
S3-01
X2
X1
Q12
D3
R38
OVEN 3
X17
S3-03
X14
X13
Q14
D6
R43



9.1 VDC
2-12
S3-BI
SSB
T
AM
S2-2
R
SI-3
12 V
SUPPLY
R49
Z4
RCVR
TX
L4
C 85
C 83
C 84
C 86
RFC4
BFO
Q16
D9
OVEN 3
X18
R48
C82

## COMPONENT LIST

| Schematic Symbol Number | Description | |
|---|---|---|
| | **Resistors** (one-half watt unless otherwise noted) | |
| R1, 3, 14 | 1,000,000 | ohm |
| R2, 17 | 100 | ohm |
| R4, 12 | 100,000 | ohm |
| R5 | 2,000 | ohm |
| R6 | 68 | ohm |
| R7 | 1,000 | ohm |
| R8 | 39 | ohm |
| R9, 10 | 10,000 | ohm |
| R11 | 6800 | ohm |
| R13 | 5,000 | ohm, variable, PC-mounted |
| R15 | 6,200,000 | ohm |
| R16 | 470,000 | ohm |
| R18 | 500 | ohm |
| R19 | 56,000 | ohm |
| R20, 51 | 2,200 | ohm |
| R21 | 1,200 | ohm |
| R22 | 5,600 | ohm |
| R23 | 18,000 | ohm |
| R24 | 3,900 | ohm |
| R25 | 1,000 | ohm, variable,panel-mounted |
| R26 | 390 | ohm |
| R27 | 27,000 | ohm |
| R28 | 510,000 | ohm |
| R29 | 5,000 | ohm, variable, panel-mounted |
| R30 | 2.7 | ohm |
| R31, 32 | 82 | ohm, one watt |
| R33 | 680 | ohm |
| R34 | 47 | ohm |
| R35, 36 | 1.5 | ohm |
| R37 | 1,600 | ohm |
| R38, 43, 48 | 22,000 | ohm |
| R39, 44, 50 | 36,000 | ohm |

| | | |
|---|---|---|
| R40, 45 | 15,000 | ohm |
| R41, 46 | 1,000 | ohm, variable,PC-mounted |
| R42, 47 | 200 | ohm |
| R49 | 100 | ohm, one watt |
| R52 | 2,700 | ohm |

<u>Capacitors</u> (disc-ceramic unless otherwise noted)

| | |
|---|---|
| C1-12, 21-32 | ARCO 424 (15-150 pF), mica |
| C13-20,34,41-43,45,46, 53,59,64-73,75,76,78-81, 86 | 0.1 uF |
| C33,47 | 1000 pF |
| C35,52 | 0.02 uF |
| C36,40 | 60 pF, mica |
| C37,39,49 | ARCO 404 (7-60 pF), mica |
| C38 | 10 pF |
| C44 | 20 pF |
| C48 | 75 pF, mica |
| C50,54 | 5,000 pF |
| C51,60 | 1 uF, 25 V, electrolytic |
| C55,56 | 10 uF, 25 V, electrolytic |
| C57 | 0.01 uF |
| C58 | 5 uF, non-polarized |
| C61 | 220 uF, 10 V, electrolytic |
| C62 | 200 uF, 25 V, electrolytic |
| C63 | 0.2 uF |
| C74,77,85 | 100 pF |
| C82 | 51 pF, mica |
| C83 | 15 pF, mica |
| C84 | 200 pF, mica |

<u>Radio-Frequency Chokes</u>

| | |
|---|---|
| RFC1-4 | 1.5 mH, 50 mA |

Audio Transformers

| | |
|---|---|
| T7 | Stancor 5603-3 |
| T8 | Stancor 5603-2 |

Torodial Transformers

| | | |
|---|---|---|
| T1 | Primary: | 2 turns, No. 25, enameled, copper wire |
| | Secondary: | 75 turns (33uH), No. 32, enameled, copper wire |
| T2 | Primary: | 2 turns, No. 25, enameled, copper wire |
| | Secondary: | 42 turns (10.5uH), No. 32, enameled, copper wire |
| T3 | Primary: | 2 turns, No. 25, enameled, copper wire |
| | Secondary: | 20 turns (2.2uH), No. 32, enameled, copper wire |
| T4 | Primary: | 105 turns (75uH), No. 32, enameled, copper wire |
| | Secondary: | 25 turns, No. 32, enameled, copper wire |
| T5 | Primary: | 16 turns, No. 32, enameled, copper wire |
| | Secondary: | 105 turns (75uH), No. 32, enameled, copper wire |
| T6 | Primary: | 13 turns, No. 32, enameled, copper wire |
| | Secondary: | 105 turns, (75uH), No. 32, enameled, copper wire |

Coils

| | |
|---|---|
| L1 | Toroid: 70 turns (31uH), No. 32, enameled, copper wire |
| L2 | Toroid: 40 turns (9.2uH), No. 32, enameled, copper wire |
| L3 | Toroid: 17 turns (2uH), No. 32, enameled, copper wire |
| L4 | Miller 4208, 120-330 uH |

Diodes

| | |
|---|---|
| D1,2 | Germanium, 1N34A |
| D3-9 | Silicon, 1N4152 |
| Z1 | Zener diode, 1N4733A |
| Z2,3 | Zener diode, 1N3828A, one watt |
| Z4 | Zener diode, 1N3019A, one watt |

Integrated Circuits

| | |
|---|---|
| IC1,2 | RCA, CA 3002 |
| IC 3 | RCA, CA 3020 |

Transistors

| | |
|---|---|
| Q1 | RCA, 3N140 |
| Q2,3 | RCA, 3N141 |
| Q4-6,8,9 | MPS 706 |
| Q7 | 2N3905 |
| Q10,11 | SE 9060 |
| Q12,14,16 | RCA, 40468 |
| Q13,15 | 2N3663 |

Filter

| | |
|---|---|
| F1 | Filtech Corporation, 1650 kHz, LSB, crystal filter |

## APPENDIX III

### RECEIVER TEST RESULTS

| | | 2.6 MHz | 5.7 MHz | 8.7 MHz | 15.3 MHz |
|---|---|---|---|---|---|
| SENSITIVITY (microvolts for a 10 db (S+N)/N ratio) | | | | | |
| SSB: | | 0.16 | 0.21 | 0.25 | 0.28 |
| AM: | | 2.8 | 1.4 | 0.6 | 0.4 |
| SELECTIVITY (kHz) | | | | | |
| SSB: | | 2.1 kHz (NOMINAL) | | | |
| AM: | 3 db | 10.0 | 7.6 | 9.9 | 5.6 |
| | 6 db | 19.6 | 12.5 | 12.3 | 9.6 |
| | 12 db | 33.5 | 22.3 | 23.9 | 14.2 |
| IMAGE REJECTION (db) | | | | | |
| SSB or AM: | | -64 | -62 | -60 | -53 |

SQUELCH CONTROL (microvolts for indicated audio output increases) — "Noise Thresholds"

| Audio Output Increases | 0.5uV | 1.0uV | 5.0uV | 10.0uV |
|---|---|---|---|---|
| 3 db | 0.18 | 0.15 | 0.2 | 0.2 |
| 6 db | 0.5 | 0.3 | 0.4 | 0.4 |
| 10 db | 0.5 | 0.6 | 0.5 | 0.6 |

CROSS-MODULATION RATIO (db)

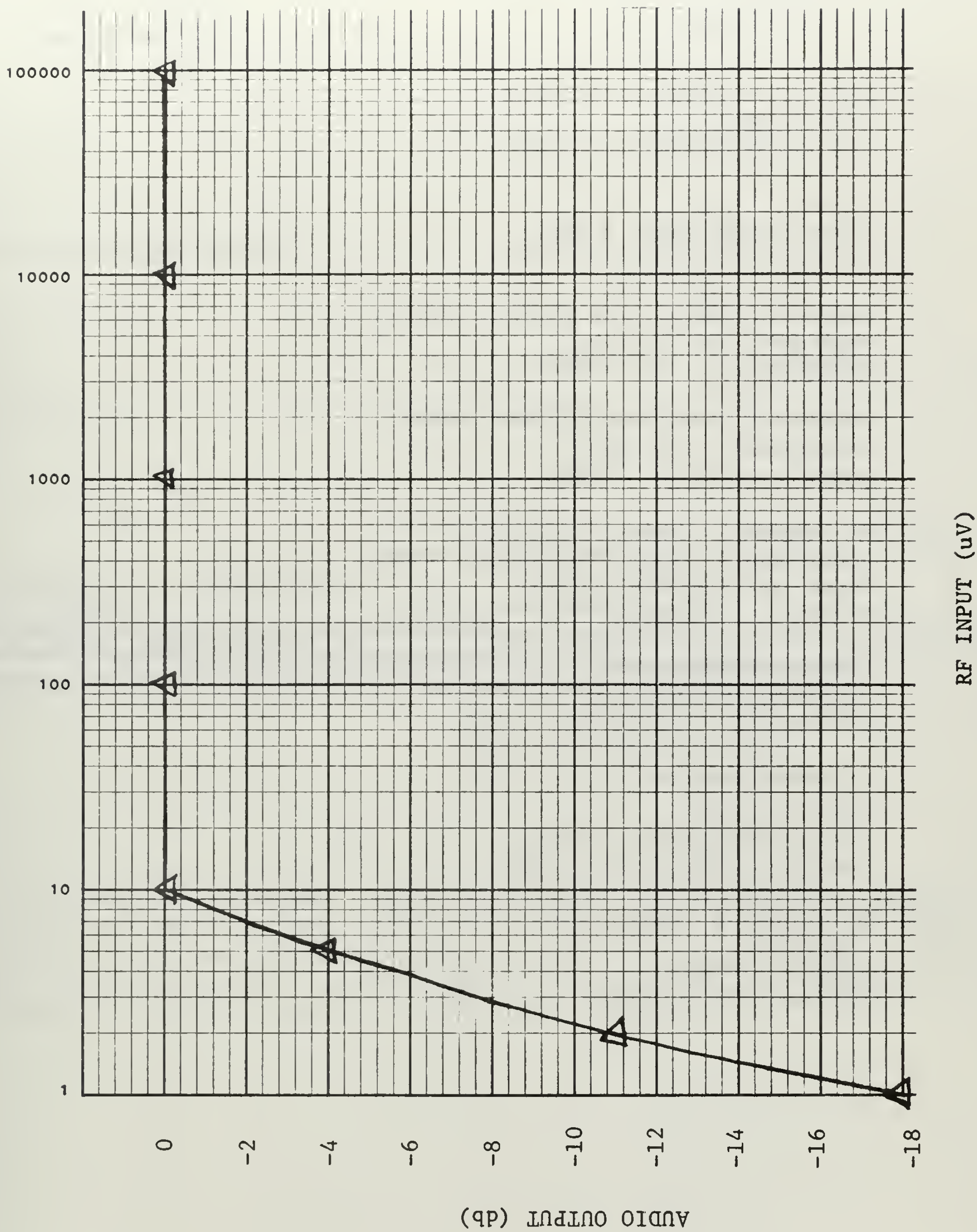
Desired signal (CW): 8705.8 kHz
Undesired signal (AM): 8710.1 kHz

| Undesired signal amplitude | CM RATIO |
|---|---|
| 1 mV | -44 |
| 3 mV | -30 |

| | |
|---|---|
| 10 mV | -20 |
| 15 mV | -10 |

INTERMODULATION DISTORTION (db)

| Audio frequencies | | IM RATIO |
|---|---|---|
| | 5.7 MHz | |
| $f_1 = 1500$ Hz | | |
| $f_2 = 1800$ Hz | | |
| $2f_2 - f_1 = 2100$ Hz | | -45 |
| | 8.7 MHz | |
| $f_1 = 1230$ Hz | | |
| $f_2 = 1370$ Hz | | |
| $2f_2 - f_1 = 1510$ Hz | | -45 |
| | 15.3 MHz | |
| $f_1 = 1500$ Hz | | |
| $f_2 = 1900$ Hz | | |
| $2f_2 - f_1 = 2300$ Hz | | -40 |




AGC EFFECTIVENESS

INITIAL DISTRIBUTION LIST

| | | No. Copies |
|---|---|---|
| 1. | Defense Documentation Center<br>Cameron Station<br>Alexandria, Virginia 22314 | 20 |
| 2. | Library<br>Naval Postgraduate School<br>Monterey, California 93940 | 2 |
| 3. | Commander, Naval Ship Systems Command<br>Department of the Navy<br>Washington, D. C. 20360 | 1 |
| 4. | Commander, Naval Air Systems Command<br>Department of the Navy<br>Washington, D. C. 20360 | 1 |
| 5. | Dr. Gerald D. Ewing<br>Department of Electrical Engineering<br>Naval Postgraduate School<br>Monterey, California 93940 | 3 |
| 6. | Linear Systems, Inc.<br>220 Airport Boulevard<br>Watsonville, California 95076 | 1 |
| 7. | LT Kenneth Bygler<br>SMC Box 1325<br>Naval Postgraduate School<br>Monterey, California 93940 | 1 |
| 8. | LT Richard W. Hamon, USN<br>c/o VA-44<br>NAS Cecil Field<br>Jacksonville, Florida | 1 |

UNCLASSIFIED
Security Classification

# DOCUMENT CONTROL DATA - R & D

*Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)*

| | |
|---|---|
| 1. ORIGINATING ACTIVITY (Corporate author)<br>Naval Postgraduate School<br>Monterey, California 93940 | 2a. REPORT SECURITY CLASSIFICATION<br>Unclassified<br>2b. GROUP |

3. REPORT TITLE

Receiver Design in a Commercial, Marine Single-Sideband Transceiver

4. DESCRIPTIVE NOTES (Type of report and, inclusive dates)

Master's thesis, September 1968

5. AUTHOR(S) (First name, middle initial, last name)

Richard W. Hamon

| 6. REPORT DATE | 7a. TOTAL NO. OF PAGES | 7b. NO. OF REFS |
|---|---|---|
| September 1968 | 57 | 10 |
| 8a. CONTRACT OR GRANT NO.<br>N/A<br>b. PROJECT NO.<br>N/A<br>c.<br>d. Distribution unlimited | 9a. ORIGINATOR'S REPORT NUMBER(S)<br>N/A<br>9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)<br>N/A | |

10. DISTRIBUTION STATEMENT

~~This document is subject to special export controls and each transmittal to foreign government or foreign nationals may be made only with prior approval of the Superintendent, Naval Postgraduate School, Monterey, California 93940.~~

| 11. SUPPLEMENTARY NOTES | 12. SPONSORING MILITARY ACTIVITY |
|---|---|
| | Naval Postgraduate School<br>Monterey, California 93940 |

13. ABSTRACT

Design of the receiver portion of a solid-state, state-of-the-art, single-sideband, 2-17 MHz transceiver is presented. A short comparison of amplitude-modulated and single-sideband systems is offered. The unique requirements of commercial, marine communications are considered and the method of their fulfillment in this transceiver is discussed. Circuitry common to both receiver and transmitter is presented in detail. Receiver testing and specific results are included.

| 14 KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Single-sideband receiver | | | | | | |
| Solid-state receiver | | | | | | |
| Marine radio | | | | | | |